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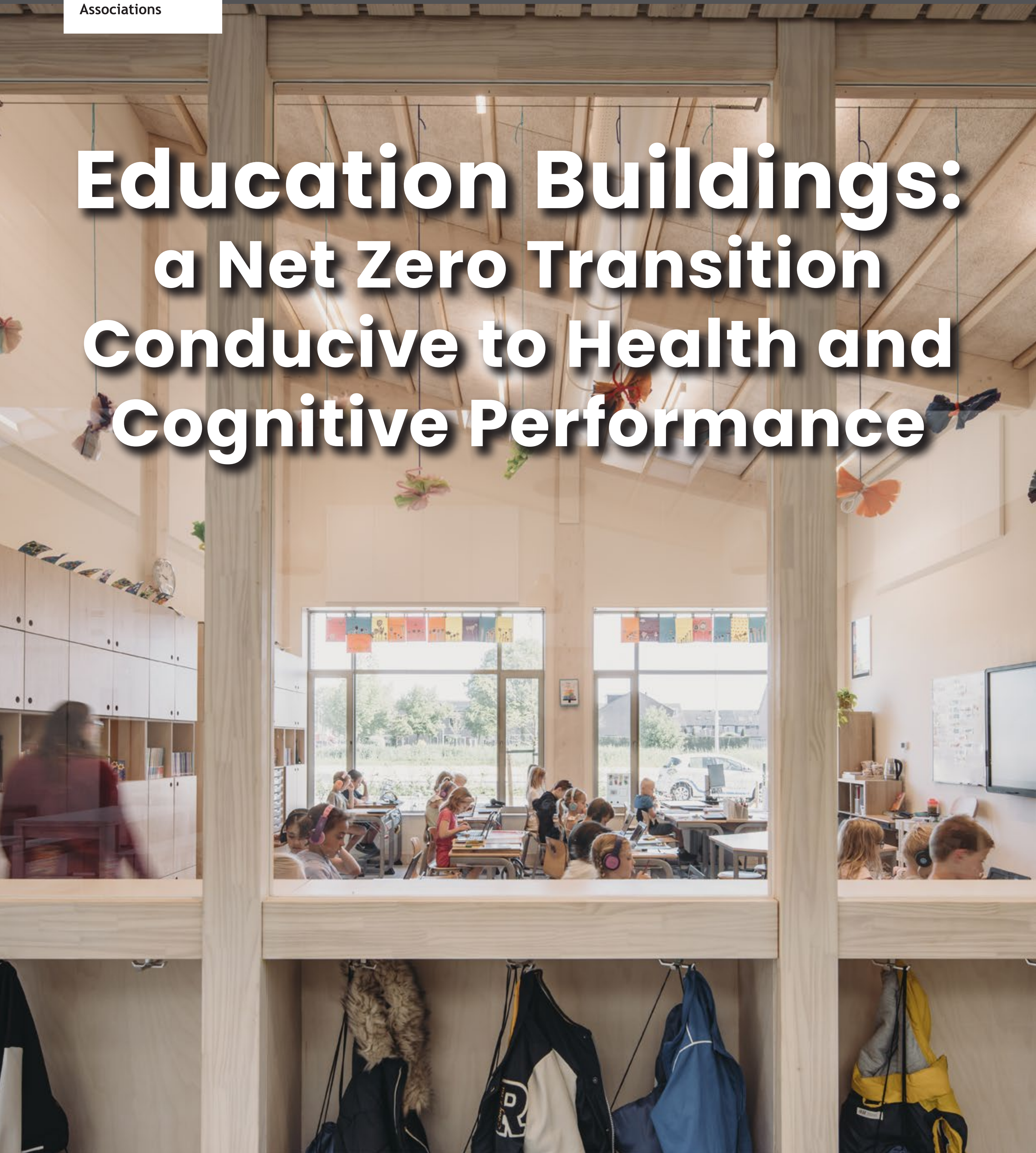
Education Buildings: a Net Zero Transition Conducive to Health and Cognitive Performance



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Liddell Road and Kingsgate Primary School, London, UK (architects: Maccreanor Lavington Architects) Atelier Ten provided environmental design, building services design, fire strategy consulting, energy analysis, benchmarking (BREEAM) and lighting design. Photo by Atelier Ten.

Education Buildings: a Net Zero Transition Conducive to Health and Cognitive Performance

Education buildings are complex, dynamic, socio-technical systems seeking to provide solutions to a multitude of ill-defined and conflicting issues including the basic truth that the built environment is fundamental to the occupants' productivity and sense of well-being and it is the totality of this idea that we need to understand and appreciate.

The past attempts to reduce carbon emissions from existing school buildings and current ongoing efforts to deliver energy-efficient school buildings conducive to learning have had little success. A decade ago, I thought that the reasons for this "underperformance" include a poor understanding of (a) how to design, engineer, and facilitate learning spaces for changing pedagogical practices to support a mass education system, and greater student diversity, (b) how pupils and teachers use energy in school buildings, (c) how pupils and teachers interact with new technology, (d) how they respond to socio-technical energy conservation initiatives, and (e) how the overall indoor environment quality affects the learning performance of pupils and productivity of teachers.

This special issue provides insights into the progress that we have made recently focusing on energy, health and cognitive performance. It starts with two think pieces: one advocating a paradigm shift in evidence-based policy making embracing climate change and cognitive performance in transition of education buildings to net zero, and the other one offering opportunities to design the robust methods for evaluating the impacts of indoor environmental quality on cognitive performance of students. The articles from Portugal, Italy, China, the Netherlands and the UK provide useful insights on decarbonisation, climate change, cognitive performance and the impact of filtration on children's health in nurseries.

I hope you find this special issue useful. Enjoy.

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Paradigm Shift in Evidence Based Policy Development for Education Buildings: Mitigation, Adaptation and School Environments Conducive to Learning

Keywords: net zero, education, sustainable buildings, climate change, cognitive performance

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Introduction

Climate resilience is not simply about withstanding physical stressors but also ensuring that the building supports human health and wellbeing. This means prioritizing indoor environmental quality, such as maintaining proper air quality and comfortable thermal, lighting and acoustics conditions which is critical in school buildings where the cognitive and physical health of occupants is at stake. The climate resilience policies focusing on school buildings illustrate a multi-layered approach: European and national bodies set the strategic frameworks and funding priorities, while implementation happens locally with tailored solutions to address the unique challenges faced by schools across different regions. To support the national governments, we need a paradigm shift in policy making incorporating all climate resilience principles: (a) mitigation, (b) adaptation, and (c) indoor environmental quality conducive to learning. This paper presents a multifaceted approach to develop a research framework that blends the physical experimentation on the effect of indoor environmental quality on cognitive performance in a controlled environment with the well-defined school building stock models. What have we achieved so far at the UCL Institute for Environmental Design and Engineering in the last decade? Are we there yet?

Decarbonisation

When looking at school building stock modelling, the two main approaches, archetype-based modelling and one-by-one (or building-by-building) modelling - offer complementary strengths and trade-offs.

Archetype-Based Modelling: This approach groups school buildings into representative categories based on shared characteristics such as construction period, building type, and usage profiles. Instead of simulating every individual building, a few archetypes are developed that capture the "average" performance of each subgroup. In England, handful of schools were built before the industrial revolution in the 19th century when the proper mass education system was established.

These schools are known as Victorian schools. Early 20th century brings the influence of German Bauhaus movement, followed by two distinctive post war periods including least loved prefabricated CLASP schools. In late 1970s, the first thermal regulatory requirements for schools were introduced and increasingly the schools' built form becomes less prescribed. The advantages include: (a) lower data requirements & computation, (b) simplicity for policy analysis or broad assessments of regional or national school stocks, and (c) ease of communication as summarized results using archetypes are often easier to communicate to stakeholders who may not be familiar with technical details. To get into details of the archetype modelling see the article written by Dr Jie Dong.

The trade-off introduced by averaging and grouping, can obscure the unique characteristics of individual schools. Variability in energy performance, school design and orientation, surrounding built environment, local microclimates, or specific operational nuances may be lost in translation. This is especially critical when optimal retrofit measures are tested with aim to increase the climate resilience.

One-by-One (Building-by-Building) Modelling: In contrast, one-by-one modelling involves creating a detailed simulation for each school building. This method harnesses granular data ranging from specific construction details, building systems' details, occupant density and patterns. The key features include: (a) increased precision, (b) potential for better accuracy, and on negative side (c) data and computational demands. **Figure 1** presents the one-by-one framework called Modelling Platform for Schools (MPS).

Modelling Platform for Schools (MPS) is an automated framework designed to generate dynamic thermal simulation models for individual school buildings. Developed by researchers at the UCL Institute for Environmental Design and Engineering, the MPS integrates diverse data sources such as building geometry, size, and the number of buildings within a school premise collected from databases like Edubase, the Condition Data Collection (CDC), and the Ordnance Survey (OC). The National Calculation Methodology (NCM) and the Display Energy Certificates (DEC) datasets are used to determine the occupancy patterns,

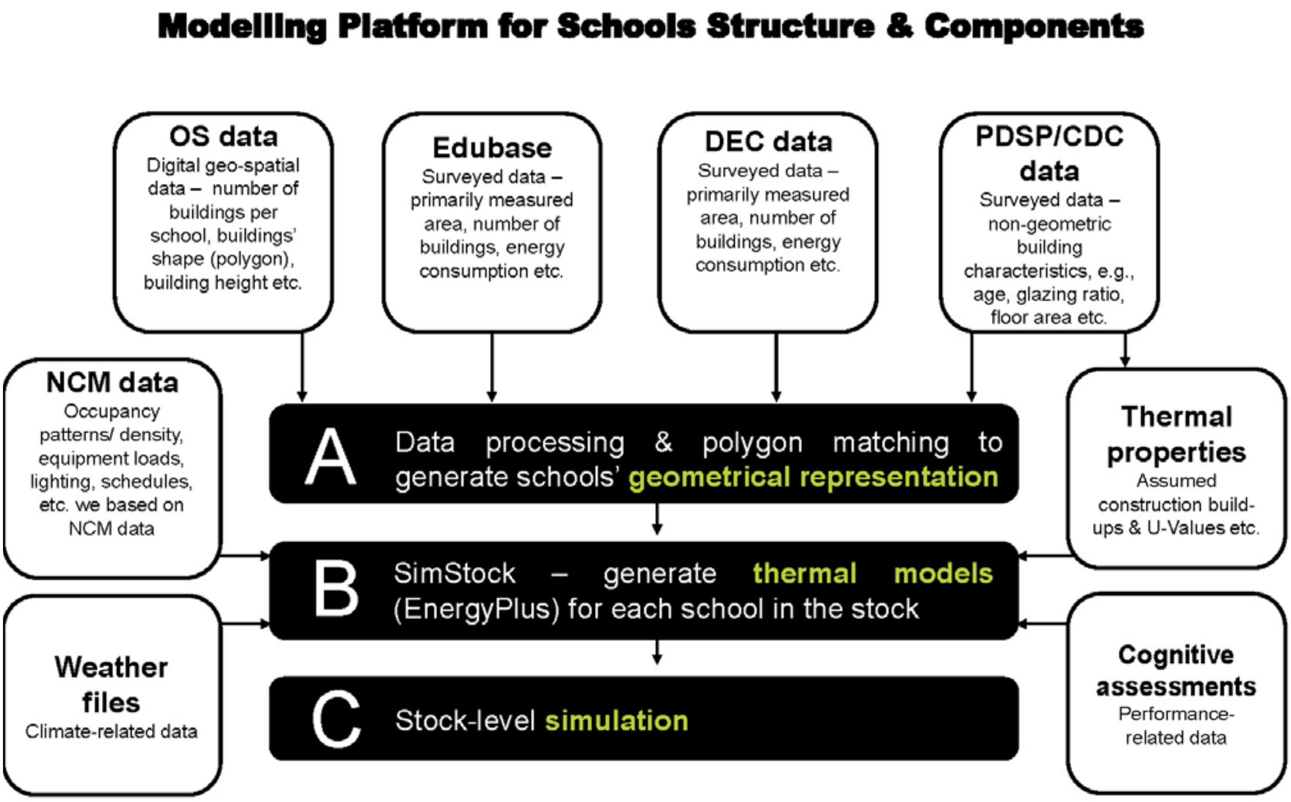

Figure 1. Data Information Flow in Modelling Platform for Schools (MPS).

occupant density, and the actual energy used intensity to validate the MPS. The MPS automatically creates 67,000 school buildings in over 22,000 schools in England with a different degree of success (traffic system is used to describe from perfect match to pay attention). A typical digital representation of schools in English school building stock are given in **Figure 2**.

By automating the creation of thermal simulation models, MPS not only facilitates a comprehensive analysis of the existing school building stock but also supports policy decisions regarding energy efficiency upgrades and retrofits aimed at reducing carbon emissions. By treating each school individually, this approach can capture the heterogeneity inherent in a diverse school stock. This is particularly useful when planning tailored energy efficiency upgrades or when specific buildings require bespoke interventions. Because it considers the exact conditions and setups of each school, the approach can potentially provide a more accurate estimation of energy consumption, thermal performance, and retrofit impacts. The downside is that gathering comprehensive data for every building is resource intensive, and running simulations for hundreds or thousands of buildings can be computationally heavy.

The decision on which method to use often depends on the study's goals, available data, and the level of detail required. In practice, if the data are available, the frameworks such as the MPS could be used in a hybrid mode: (a) archetype-based approach work well for national policy and broad strategy for decarbonisation building stock, and (b) : one-by-one modelling for tailored interventions and detailed analysis when the objective is to identify the specific characteristics and retrofit needs of individual school buildings. Despite, the archetype-based models are still predominantly used, the use versatility of the one-by-one building stock models, and increasing data availability will lead to their widespread use in future.

Cognitive Performance

As stated above the climate resilience strategies require the holistic approach beyond the energy use intensity and carbon emissions (operational and embodied). Multiple studies have demonstrated that both indoor temperature and ventilation significantly influence the cognitive performance of students. Research has indicated that there is an optimal temperature range—commonly around 19 - 23°C where students perform best on cognitive tasks. Deviations from this range upwards can lead to discomfort, lethargy and students might have difficulty focusing on complex tasks, which can diminish overall academic performance. Conversely, environments that are too cold can also disrupt attention and comfort, underscoring the need to strike a balance for optimal learning conditions. Poor ventilation often leads to the accumulation of CO_2 (as a proxy for ventilation rates) which has been correlated with symptoms such as headaches, drowsiness, and reduced concentration – all factors that can impair cognitive function (lot of academic papers do not differentiate CO_2 as a proxy for ventilation rates or as a pollutant on its own right; please read the paper produced by Dr Ben Jones for this issue who provide a criticism of the current built environment research in this field).

By optimizing thermal comfort and indoor air quality, schools can create a more conducive learning environment that supports robust cognitive performance, thereby enhancing overall academic outcomes.

What we need to know? Cognition refers to the mental processes related to knowledge which occurs in the brain, comprising attention, memory, learning,

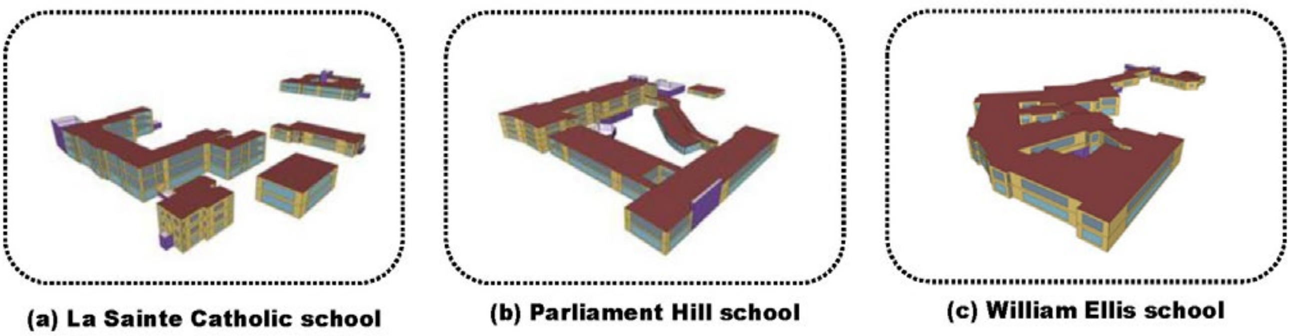

Figure 2. Typical automatically generated school geometries.

language, reasoning, problem solving, decision making, perception and a host of other vital processes. The measurement of cognition can be conducted through a range of methods, each differing in terms of their degree of objectivity and sensitivity.

It is essential to understand that unlike learning outcome which "belong" to an individual's performance in tasks and/or subjects, cognitive performance offers a broader and more enduring quantitative assessment of one's cognitive ability, transcending learning contexts. To integrate the cognitive performance functions in the building stock models we need robust studies carried out in controlled environments, so we can link the outputs of the building simulations with the relevant cognitive performance functions. In my view the studies based on learning outcomes should not be coupled with the school building stock models, as learning is far away more complex phenomenon. A typical experimental process is shown in **Figure 3**.

The development of computer technology has led to the development of several computerised cognitive testing batteries. Computerised cognitive tests have been created and verified to target specific brain regions, offering numerous advantages compared to traditional pen and paper methods. In addition to teasing apart different cognitive domains, data collection can be automatic process, thereby minimizing the potential for errors and influence of administrator bias. Computers can enable precise recordings, such as highly accurate measurement of response latencies. The implementation of standardised assessment and the flexibility to adjust difficulty levels of computerized cognitive tests effectively minimize the floor and ceiling effects. While cognitive performance does not have standard "units" like physical measurements (e.g., temperature), speed (how quickly each pupil worked per unit of time) and accuracy (expressed as a percentage of possible errors) are typically used as the main indicators to characterize students' performance in different cognitive tasks. They are often expressed as a relative value such as CPL (Cognitive Performance Loss, see the article written by Dr Jie Dong).

At the UCL Institute for Environmental Design and Engineering we use the Behavioural Assessment and Research System (BARS), but in principle the advantages of cognitive test batteries (SMS, BARS, NATB) over traditional cognitive tests: (a) have proven validity in measuring cognitive performance in a variety of domains, (b) are often standardized, which can make them less susceptible to bias, (c) can be administered by personnel with limited training, and (d) cover a wider range of domains associated with education. **Figure 3** proposes a set of cognitive performance tests suitable for learning environments (some simplifications might be possible, but more evidence is required). For detailed description see the article written by Dr Didong Chen in this issue.

Based on our experience on evaluation of cognitive performance of students in controlled environments (based on the doctoral work carried out by Dr Riham Ahmed, 2016, Dr Didong Chen, 2025 and Dr Zeyu Zhao, 2025) to enable the integration into the school building stock simulation the experimental studies must:

1. be well documented including the study design, ethics approval, execution, data analysis including access to the data created via open access platforms such as GitHub
2. conduct a robust sample size calculation prior to the experiment to ensure enough statistical power of the research findings

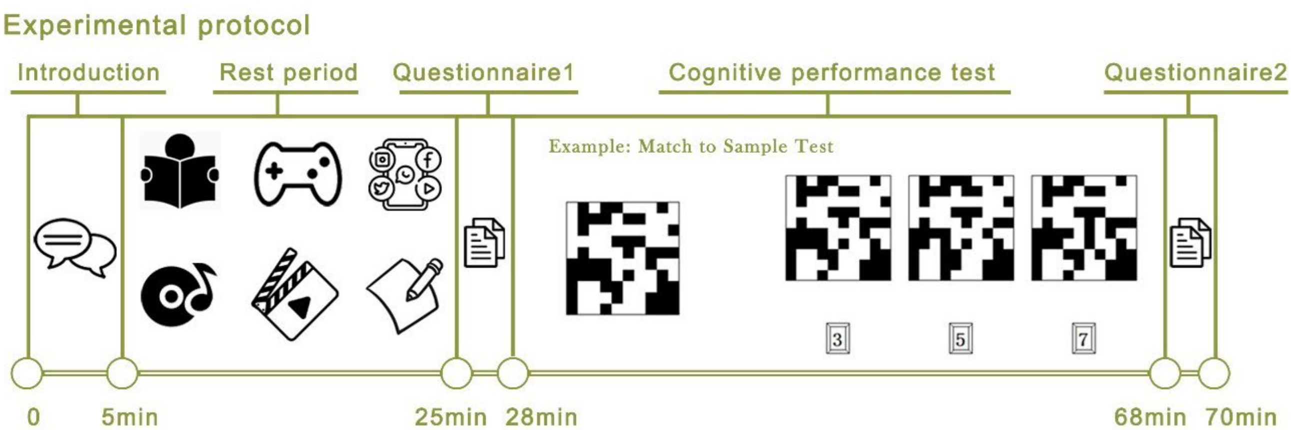

Figure 3. Structure of a typical experimental protocol.

3. implement a validated cognitive test battery measuring a wide range of cognitive domains of importance to learning
4. control for factors like age, gender, acute exercise, sleep, and caffeine which have long been associated with individuals' cognitive functioning
5. to account for confounding factors, ensuring that either temperature, ventilation rates and/or any other parameter is the sole independent variable. If this is not possible, investigations should strive to quantify and disclose the variability in confounding factors, enabling researchers to determine whether these factors are likely to affect the cognitive performance outcomes or not
6. testing one individual alone in the chamber might be a better solution as one participant might be impacted by another when taking the cognitive test.

When comparing the results from prior research, different cognitive tests were used to measure cognitive performance, each test might be associated with several cognitive domains, which makes it difficult to reach a definite conclusion by comparing the results like-for-like based on individual tests. Interpreting the findings from an aggregated perspective is necessity before the academic community reaches consensus.

Techniques such as electroencephalography (EEG), heart rate monitoring and fMRI provide researchers with means to deeply understand and assess cognitive performance by evaluating physiological and psychological response mechanisms. Not applied to the built environment research too often, so more trans-disciplinary approach might become a norm in future years. Although not directly required for integration in the building simulation models, this might further improve the robustness of the cognitive performance functions required.

Climate Change

Existing English schools will continue to operate for years in the future, many of which lack the consideration for climate change in terms of construction and operation. CIBSE (Chartered Institution of Building Services Engineers) provides specialized weather data files that are essential for climate-resilient building design in the UK. CIBSE offers future weather files based on UK climate projections (UKCIP09), covering (a) time periods: 2020s, 2050s, 2080s, (b) emissions scenarios: low, medium, high, and (c) percentiles: 10th (cooler), 50th (median), 90th (hotter). These are currently available for 14 UK locations and are structured to support simulations under different climate futures. For high-resolution (2.2 km) climate change weather data in the UK, CIBSE is testing the new set of weather files based on the UKCP18 local projections (2.2 km) which should be implemented in future.

Based on the archetype model of English school building stock developed at the UCL Institute for Environmental Design and Engineering, Dr Jie Dong estimated the frequency distributions of hourly Cognitive Performance Losses (CPLs) in English schools per region during non-heating school days (**Figure 4**). Note that schools in Southern England have minimal hours categorized as 'No loss' and 'No significant loss' in future climates both of which are much higher than those in the other two regions. Having this in mind all mitigation and adaptation policies should consider regional differences.

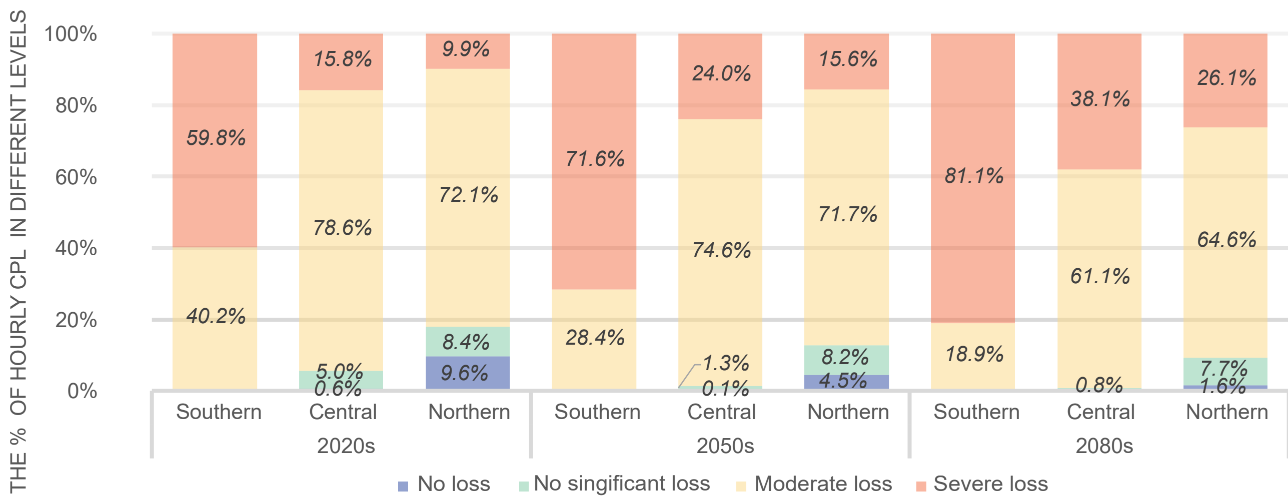

Figure 4. The frequency distributions of hourly CPLs within different levels in English schools per region during non-heating school days.

Finally, the **Figure 5** shows the potential of air conditioning as an active adaptation measure in reducing cognitive performance loss of pupils in insulated schools. The median values of cognitive performance loss and the corresponding cooling loads at set point temperatures of 21°C and 25°C in schools across all three regions of England highlight significant increase in the cooling load in Southern region of England with climate change if cognitive performance loss is to be maintained at levels conducive to learning. Unfortunately, at the time of writing this paper the impact of decarbonisation on climate change and cognitive performance has now been analysed yet, but the architype modelling set up the trends and challenges that we will face on transition to net zero.

Delivering a Paradigm Shift in Evidence Based Policies

The climate resilience and adaptation have gained interest not only from building experts, but also from educationalists and policymakers in the education sector. To support the national governments, we need a paradigm shift in policy making incorporating all climate resilience principles: (a) mitigation, (b) adaptation, and (c) indoor environmental quality conducive to learning. One-by-one modelling approach is versatile to cater for both, tailored interventions and detailed analysis when the objective is to identify the specific characteristics and retrofit needs of individual school buildings, and if aggregated at the national and regional levels to form basis for the evidence-based policy making and the strategy development.

However, stakeholders without building expertise may struggle to fully comprehend the outcomes of building performance assessments based on traditional engineering key performance indicators such ventilation rates, operative, air or radiant temperature, and the implications of these outcomes on cognitive performance of children in classrooms. Using cognitive performance loss as the knowledge performance indicator to describe the climate resilience of schools offers a means of using language that can be understood by non-building experts, facilitating the interpretation and communication of research findings to the intended audience.

Acknowledgments

This think piece is based on synthesis of work carried out by a large team of my colleagues and doctoral researchers in the last 15 years. Special thanks to Dr Jie Dong, Dr Duncan Grassie, Dr Didong Chen, Dr Zeyu Zhao, Dr Riham Ahmed, Dr Greig Paterson, Dr Sung Min Hong who were awarded their PhDs on the various aspects of the work on education buildings used to develop the ideas presented here. Also, many thanks to the core team of academics and postdoctoral researchers that I have worked with on these topics especially the core team members: Dr Ivan Korolija, Dr Yair Schwartz and Daniel Godoy Shimizu.

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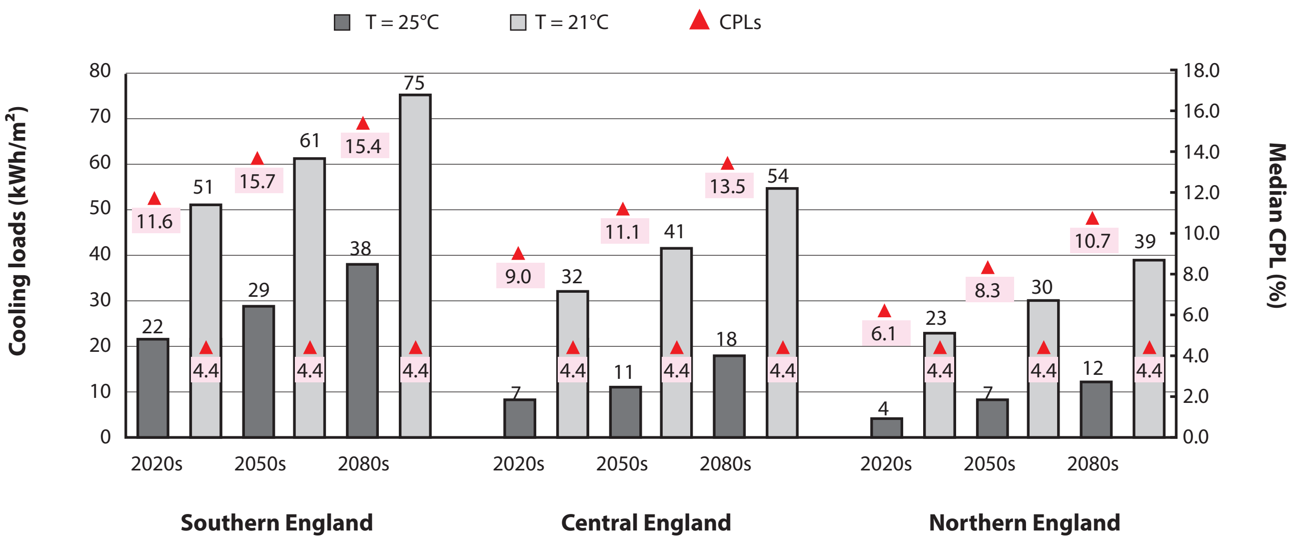

Figure 5. The comparison of cognitive performance loss and corresponding cooling load at the set-point temperature of 21°C and 25°C.

Forthcoming Technical Guide: CIBSE TM57 Integrated School Design

Keywords: schools, design, TM57, technical guide, CIBSE

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A team of around 30-40 academics, policy makers and industry experts have recently come together to significantly update CIBSE's Technical Memorandum (TM) on school building design, known in shorthand as TM57. Since this document was first published in 2015, there have been significant terminological, technological and regulatory changes in the sector. Hence updates to chapters were deemed necessary to existing chapters such as heating, energy, control systems and overheating, as well as entirely new sections including indoor air quality, low carbon case study, inclusive and biophilic design.

The document begins with describing the overarching design process, illustrated in **Figure 1**. This provides the design team with a framework to integrate interlocking

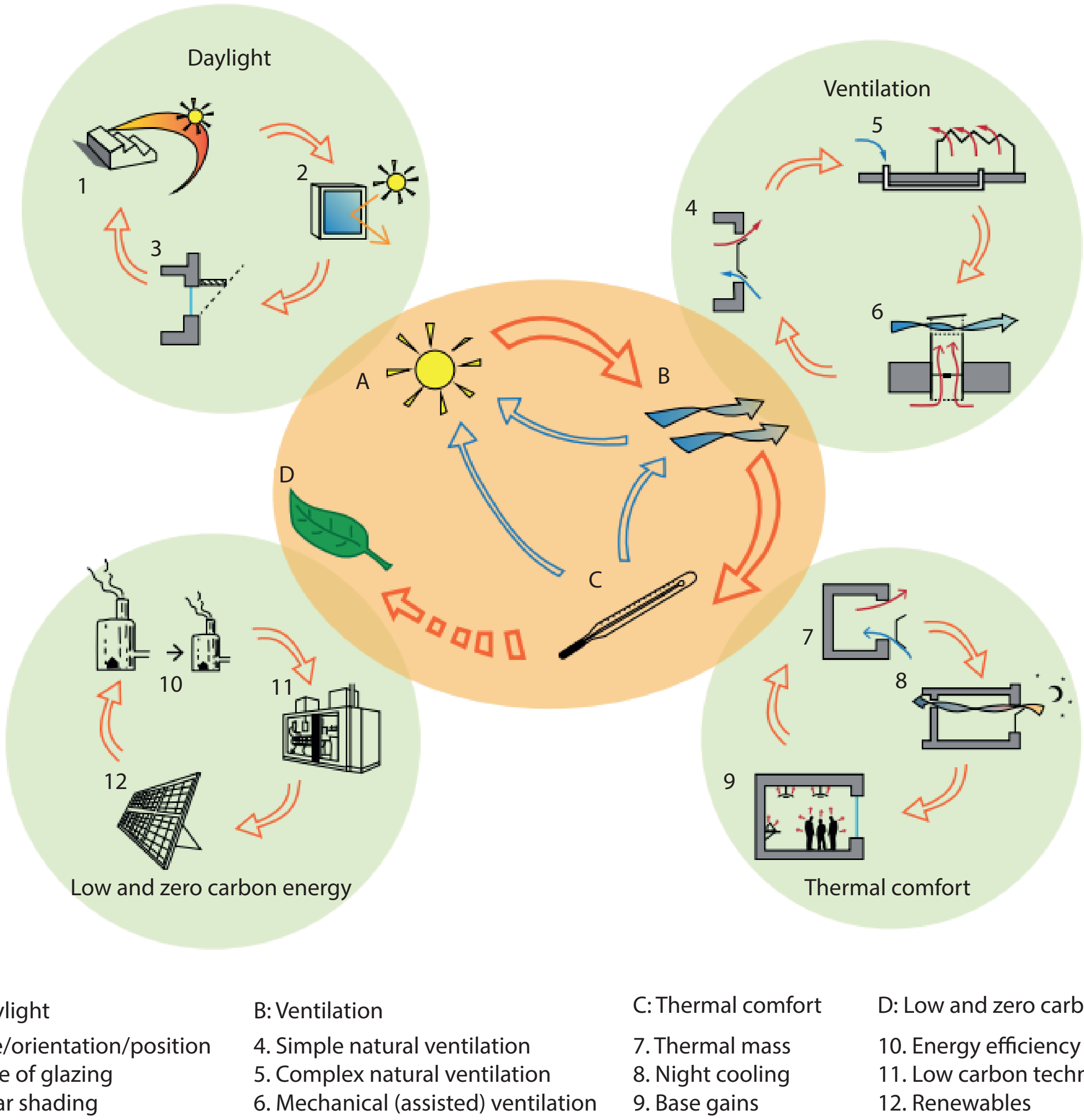

Figure 1. The impact of design solutions on teaching and learning in schools.

and often contradictory briefs on educational outcomes, technical and operational requirements and cost, with RIBA's Plan of Work as a spine (RIBA, 2021). Fostering and empowering an "informed client" to act as a bridge between future educational/operational needs and the current design is also critical to this process. Performance-in-use metrics are summarised in this chapter to give professionals a means of optimising performance across a range of factors. Inclusive design is also highlighted as a requirement to make the reasonable adjustments for disabled students, guaranteed through the Equality Act (2010), and a list of standards are provided to ensure compatibility.

Individual aspects of Indoor Environment

Following a section demonstrating early engineering considerations to overcome interrelated conflicts, the rest of the document summarises the different requirements for various individual aspects of school buildings beginning with Indoor Environmental Quality aspects of acoustic, lighting, indoor air quality and thermal comfort.

Critical factors relating to acoustic performance, as shown in **Figure 2**, are often considered too late in the design process to influence architectural layout and material selection, requiring remedial work. Hence the acoustic chapter in TM57 describes possible solutions to a number of design and operational requirements which can conflict with the provision of acoustic performance. These include heat pumps, which although necessary for planning of BREEAM credits, even when located outdoors can prevent effective use of ventilation or even indoor teaching spaces themselves. Similarly, with daylighting, methods to keep heat out of classrooms may unintentionally prevent the ingress of natural light; TM57 describes a number of daylight distribution systems, such as light wells and clerestory windows which maximise ingress while minimising glare.

Successful school ventilation strategies balance a complex set of interacting factors, including maintaining safety and security while minimising noise ingress. Thermal comfort, indoor air quality (IAQ) and heat loss are the most significant factors to be balanced with ventilation so the middle sections of TM57 considers these factors in consecutive chapters. Following the post-Covid mass installation of carbon dioxide (CO_2) sensors, the ventilation chapter describes advantages and disadvantages of the use of carbon dioxide as a popular proxy for ventilation quality. Differences are identified in how mechanical, natural and mixed mode ventilation systems can be used appropriately to ensure compliance with ventilation and heating guidelines such as Building Bulletin 101 (DfES, 2018). Although a comprehensive list of natural ventilation strategies are retained from 2015, a new section for 2025 covers corresponding mechanical ventilation strategies such as centralised vs localised systems and use of peak lop cooling using heat pumps.

Although overheating is the first of three ventilation-related impacts to be addressed, methods to manage overheating risks themselves should be implemented in the correct order, hence a cooling hierarchy has been described (see **Figure 3**), showing the correct order to enact various passive and reactive responses. Resilience of UK school buildings, as insulation and air tightness are increased to address climate change, as well as for future climate scenarios, is a key recent addition to overheating assessment. As well as a description on the practical operation of, and performance evaluation of ceiling fans, recent work on effectiveness of other passive methods such as nighttime ventilation and shading is presented. A brand new IAQ chapter summarises source, design, urban and meteorological factors which can exacerbate ingress or generation of pollutants indoors before providing a hierarchy of mitigation methods. Most relevant developments here

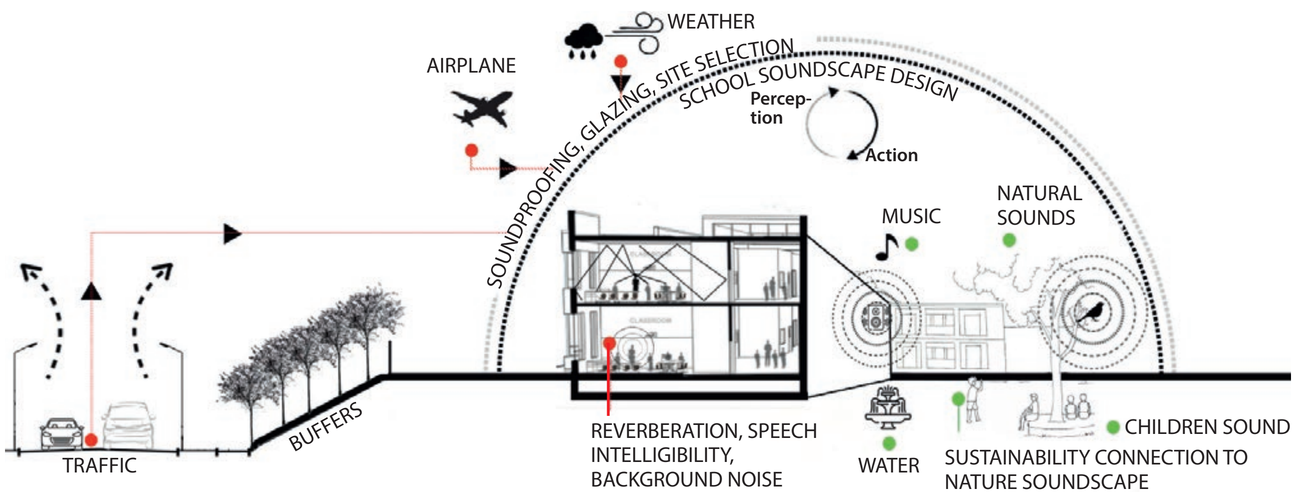

Figure 2. Summary of factors influencing acoustic performance.

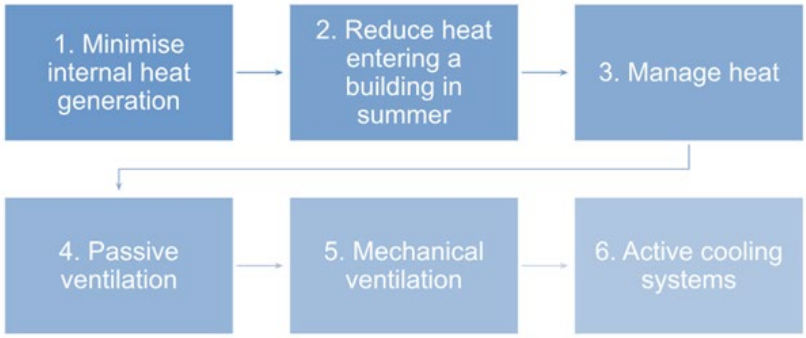

Figure 3. The cooling hierarchy.

include a comprehensive description of indoor sources from World Health Organisation reports (WHO, 2022), moisture control tools to prevent mould and case studies on how to ventilate airtight near zero carbon schools.

Design, control and monitoring of heating and other building services.

The heating, cooling and hot water section provides a bridge from ventilation into controls, environmental and energy sections. Recent concepts which are introduced here include the more stringent Building Regulations Part L concerning construction while minimising energy and carbon consumption, as well as solutions such as thermal storage and Thermally Activated Building Structures (TABS). Heat scavenging is of articular relevance in 2020s schools, due to the increasing prevalence of server rooms and a case study of a Net Zero Carbon in Operation (NZCiO) school is provided to show how thermal performance has been improved in practice.

The controls section outlines best practice for service controls incorporating heating, ventilation, environmental and lighting systems, as well as what is required in building regulations. However much of the focus lies on key considerations of building users with different capabilities and considerations, from facilities managers to pupils themselves. As well as describing different modes for heating, lighting and ventilation control systems to address these differences, implications for documentation, complexity of controls and graphical user interfaces (including alarms) have also been considered. As with the design considerations above, references are made to the different stages within the RIBA Plan of Work, focussing on the handover in Stages 3 and 4.

A new chapter on Biophilic design describes the rationale as well as examples of key features such as green walls, green roofs and rain gardens which can be incorporated into school building design to provide connection between building user and the natural environment. The concept of the Flourish Model (Clements-Croome, 2021) is introduced which has been associated with stimulation of relaxation alpha brain waves and lowering of stress beta waves (**Figure 4**).

As well as updating metrics for Energy Use from the 2015 version based on technological and operational changes, the Energy chapter describes how to include 'Zero' Carbon into operational design, based on repurposing the existing estate. A major conflict here is that often condition and improved energy performance funding are available separately, however a dual approach to improve both simultaneously should be sought. A five-step carbon hierarchy, involving engagement with building users, reduction in demand and wastage and decarbonising and neutralising supply, is provided to ensure all issues relating to energy efficiency are dealt with first before tackling carbon emissions. A description of Post Occupancy Evaluation (POE), as a means of systematically investigating a school's operation before making performance improvements is therefore a logical follow-on from energy. This chapter encourages designers to go beyond what is specified in the DfE's Output Specifications Technical Annex 2K (DfE, 2021).

The best-practice part of the document concludes with the facilities management chapter, relating to the documentation and training required to effectively handover the building to a site manager for the operations phase. The major challenges of this phase are that there is no one-size-fits-all definition of the site manager role, and quite often there is no single person responsible for delivering the teaching environment, with teachers and even students also involved in learning environment control. Zoning, extended occupancy outside of school hours, and use of monitoring equipment are also covered in some detail.

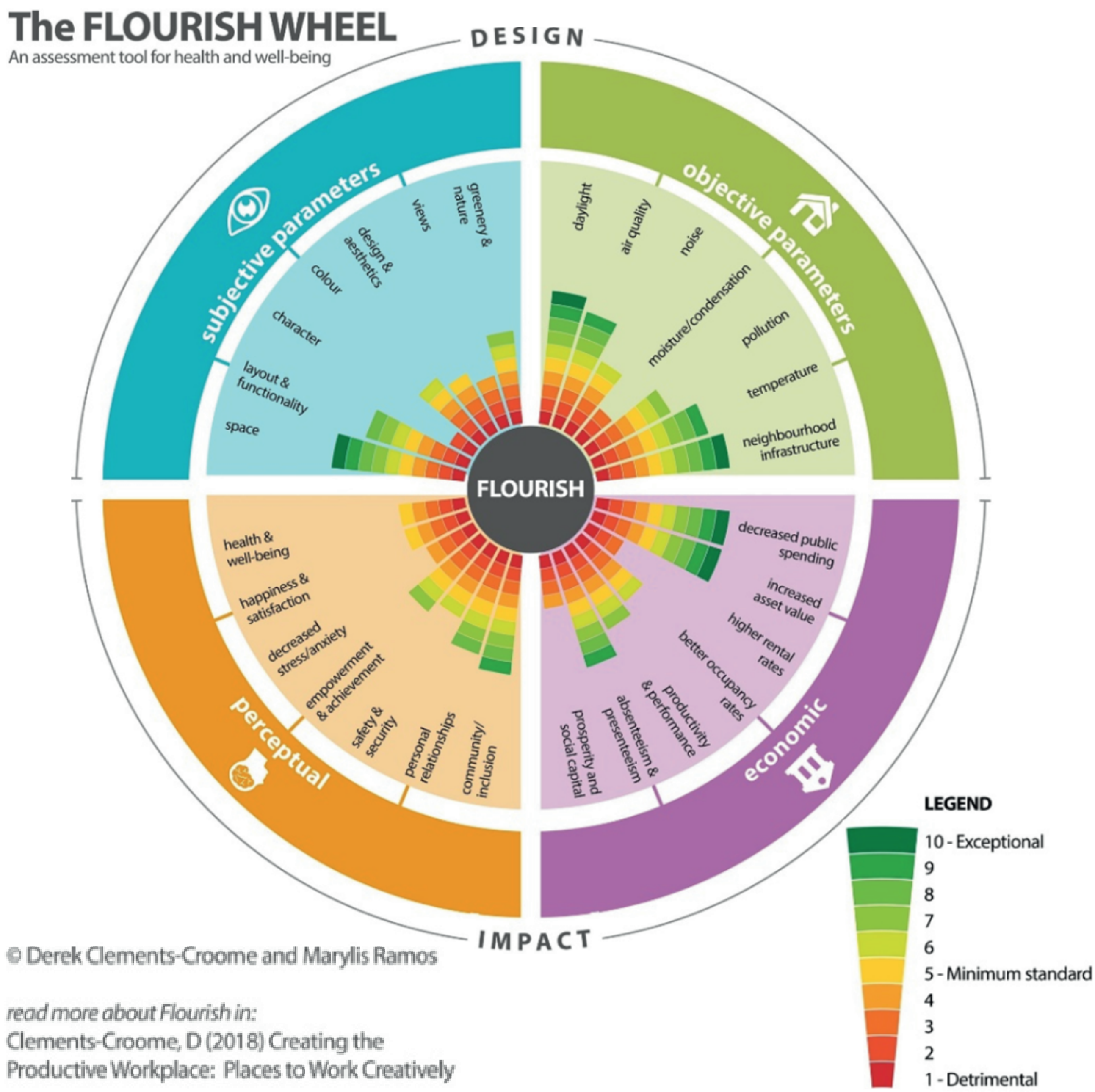

Figure 4. The Flourish Wheel. (Clements-Croome 2021)

Use of case studies in TM57

TM57 utilises case studies in three main ways:

1. Examples of best practice specific to a certain aspect of school building design (e.g. acoustic performance) presented within a specific chapter
2. Two integrated case studies, presented in standalone chapters representing a Modern school (retained from 2015) and a newly added Passivhaus school, showing how design can incorporate the range of aspects presented in each chapter.
3. An addendum of case studies bridging both individual aspects and integrated design and not limited to best practice will be provided separately to the main document, which will be updated and added to as time goes on. These are best categorised as lessons learned examples.

It is hoped the mixture of best practice, integration of a number of aspects and lessons learned provide a realistic view of school design in practice which complements the main document and can be updated more frequently so that readers are not left waiting for another decade to understand the most up to date design specifications.

References

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Clean Air, Cloudy Evidence: What Do We Really Know About Ventilation and Learning?

Keywords: IAQ, educational buildings, cognitive performance, learning

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We have a duty to protect the vulnerable, and that includes the children who spend over a thousand hours each year in classrooms. For those of us working in ventilation, that responsibility often translates into a push for cleaner air.

During the COVID-19 pandemic, some ventilation engineers became household names in their own countries doing amazing jobs of making people aware of the importance of IAQ. CO_2 sensors and HEPA filters were installed in classrooms across the globe. Since the pandemic, there has been renewed interest in improving IAQ in schools, fuelled by concerns about infection, but also by wider pre-existing claims about the health risks from contaminant exposure, and the effects of IAQ on attendance, cognition, and academic performance.

Advocates now campaign for ever higher airflow rates, often invoking the language of safety and science. But not all evidence is equal. And beyond a certain point, more air does not always mean more benefit. The concentration of a contaminant is inversely proportional to the clean airflow rate, and so there is a law of diminishing returns where the benefits gained from increasing the airflow rate represent a proportionally smaller gain as more is added. This is illustrated in **Figure 1**, although it should be noted that the space conditioning load can be eliminated if secondary air systems are used, such as portable air cleaners. When the concentration of a contaminant of concern is in the left half of the plot, where the concentration gradient is steepest, it may be desirable to reduce its concentration. But when it is in the right side where the gradient is small, it may not be worth it. There are often many contaminants of concern present in indoor air and, for a particular airflow rate, they may be in different parts of the plot. During the COVID-19 pandemic, this plot was used explain to policy makers why it is important to treat under-ventilated spaces first, and why a blanket approach to all spaces everywhere is sub-optimal.

There is a strong health-based justification for ensuring acceptable IAQ in schools. This means meeting existing standards and guidelines. But going beyond

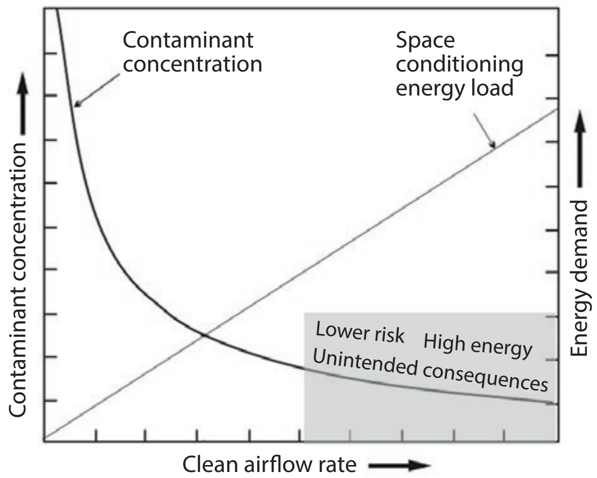

Figure 1. The law of diminishing returns: the relationships between contaminant concentration, energy, and the clean airflow rate.

that requires major investments in system upgrades, or the widespread deployment of air cleaners, and so it would demand strong evidence.

What is Indoor Air Quality?

A General Definition

A definition of indoor air quality is often a subject of tension. Most would agree that the phrase 'indoor air' considers air in a building and immediately around it, which may be brought inside. It is the word 'quality' that is contentious. Quality is a measure of excellence. It is a relative parameter. A horse was considered an excellent mode of transport until the car was invented. So, when we think of IAQ, it is relative to something. But considering the quality of indoor air relative to uncontaminated air may not be an efficient approach because it may cause resources to be expended on the unnecessary design, manufacture, and running of systems. So how should we think about IAQ? Should we strive for the best, the most excellent quality? Or, should it be good enough? Should it be acceptable? What would make IAQ acceptable?

ASHRAE defines *acceptable* indoor air quality as "air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ASHRAE 2022). Acceptability is not a categorical outcome (bad, average, good, excellent), as some experts often mistakenly say it is. It is firmly binary: the quality is either *acceptable*, or it is not. It is the criteria of acceptability that might change as new evidence emergences, improving IAQ. EN16798-1:2019 also talks about acceptable IAQ but does not define it. IAQ is implicitly considered acceptable when the IAQ criteria for a space are defined and then achieved. This is our current paradigm.

Dose and Response

Any person is exposed to airborne contaminants when they occupy the same space as contaminated air and their exposure is a function of the concentration and the time spent in the space. The dose received is a function of breathing rate, breath volume, and uptake by the lungs (Jones et al., 2021). These factors are affected by metabolic rate and physiology that may be a function of age and sex (Persily 2017). None of these parameters are constants and so the dose received in different spaces and for different occupancy scenarios will also be different. Small children respond differently to young adults. Therefore, an air quality metric should identify when the quality of indoor air is unacceptable and should be based on its effects on human health and comfort.

A person's responses to a dose may be immediate and are known as *acute* responses. We have tended to categorise these responses as a *building related illness* when we know the cause, or as *sick building syndrome* when we don't. We know some contaminants cause acute effects and the world health organization (WHO) regulates $PM_{2.5}$ (particles with a diameter of less than 2.5 microns), PM_{10} (particles with a diameter of less than 10 microns), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2) and formaldehyde (HCHO) over a 24-hour period. This is because there are established correlations between the presence of these contaminants and negative health effects. However, we cannot yet say, and may never be able to say, that a specific health outcome is likely at a given contaminant concentration, such as a child suffering an asthma attack at some $PM_{2.5}$ concentration.

Responses that act over a lifetime are known as *chronic* responses. The harm caused by years of exposure may be illness, disability, and/or premature death. The WHO regulates $PM_{2.5}$, PM_{10}, and NO_2 over an annual period.

How Might we be Wrong?

Rethinking the Regulation of Contaminants

An exposure limit value (ELV) is the highest amount of a substance considered safe to breathe over a certain period, based on current health evidence. They are used in occupational environments to prevent or reduce risks to health from hazards, such as vibrations, by setting a maximum quantity experienced over an exposure time. A problem with them is that it isn't clear how a change in an ELV, say by 10%, would affect occupant health. This can only be done with knowledge of the dose-response relationship.

ELVs are given by regulatory authorities for criteria contaminants that are known to have a direct effect on human health, but they don't agree with each other. For example, the WHO and the US environmental protection agency give wildly different ELVs for the same contaminants, such as $PM_{2.5}$ (USEPA 2024; WHO 2021). If both organizations consider the same risk of harm, they should agree. There is also harm inequity between contaminants, because exposure to different contaminants at their respective ELVs should result in the same level of harm from each. The selection of ELVs is generally undocumented and subjective. A further problem is that there are often many criteria contaminants in standards and guidelines; for example, the UK's school IAQ guideline document, BB101, gives ELVs for 16 contaminants (DFE 2018). Prescribing lists of ELVs is unwise because a diagnostic procedure is required for each of them, and time and cost constraints make enforcing the list impossible. It makes more sense to identify contaminants based on the dual conditions of being harmful and commonly present in indoor air. Then contaminants can be ranked by the harm they cause and the most harmful targeted for mitigation. The econometric of harm used, the disability adjusted life year (DALY), allows the harm from each contaminant to summed to estimate the total harm caused by all airborne contaminants (Morantes 2024). The total harm in DALYs can then be compared against DALY values for other common hazards, such as transport injuries or smoking.

This type of harm analysis has now been done for homes and offices (Morantes et al., 2024). In homes, of the 45 evaluated, six contaminants were found to cause 99% of the total harm: $PM_{2.5}$ (~66% of all harm), $PM_{10-2.5}$ (~13%), HCHO (~9), and NO_2 (~8%), radon (~2%), and O_3 (~1%). These are the most harmful contaminants by around an order of magnitude. In offices, five contaminants cause 99% of the total harm: $PM_{2.5}$ (~93%), HCHO (~5%), and O_3 (~1%). The population harm from exposure to airborne contaminants in homes is over 7 times higher than offices. Would we expect to find the same schools? Airborne contaminants in school classrooms generally originate from outside, so it is very likely that the contaminants identified for offices will also be important, particularly PM, although the proportions each contributes to the total harm will be different. The air in homes is likely much more harmful than in schools because there are prominent contaminant sources in homes that do not exist in school classrooms, such as cooking, and because children spend more time at home.

The Mirage of Causal Claims

Ventilation and air quality are increasingly promoted as levers for improving academic and behavioural outcomes in educational buildings (Allen 2021). But much of the supporting evidence comes from observational studies that are not designed to establish causality. There are many observational studies, where researchers watch what happens in real life without trying to change or control anything, which demonstrate some effect of ventilation on some measure of productivity or cognitive ability. However, they are often conducted over relatively short periods, and it is not possible to extrapolate the effects over longer periods or identify what metrics of productivity improvement might be expected. These studies often poorly control for confounders like age, sex, sleep, nutrition, noise, and teacher quality, or attempt to account for everything in models built on small samples whose statistical power is low so that the chance it detects a real effect when there actually is one, is also low. The results are inevitably noisy. In some cases, the observed effect of IAQ on test performance is smaller than the natural variability in the test scores themselves.

The literature is littered with examples of what were originally perceived to be correlations to improved productivity, which over time are discovered to not be causal at all. The most famous is the Hawthorne Effect, where research suggested that productivity at an Electric Works was increased by improving the lighting levels in the factory, a conclusion that was later found to be false because the workers had modified their behaviour when they are aware of being observed (Levitt 2021). Without robust data and studies there is a likelihood that reported correlations may not have any causative features related to the ventilation rates.

One common pitfall is the overuse of CO_2 as a proxy for indoor air quality (ASHRAE 2025). While it can serve as an indicator of the ventilation rate in some circumstances, CO_2 is not harmful in a typical classroom. It is not an indicator of IAQ because its concentrations are uncorrelated with other contaminants. This is because it is solely diluted by outdoor air, whereas PM, HCHO, O_3, NO_2 and airborne pathogens have multiple removal mechanisms. Yet, it dominates many analyses. This has skewed both academic discourse and public messaging. Claims that cognitive performance improves at lower CO_2 concentrations are often built on weak data and unvalidated tests, sometimes conducted over short periods or with repetitive online formats that risk disengagement.

One example is a recent study that measured CO_2 in university lecture rooms and tested students' cognitive performance after class using a Stroop task (Dedesko 2025). The researchers found that higher CO_2 was linked to slightly worse test results. But an examination of the method shows the evidence is weak. The study was underpowered, with only 54 students completing enough tests, which is about half the number the researchers had planned. The rooms were also fairly well ventilated, with CO_2 mostly below 1,200 ppm. Nevertheless, the analysis focused on the upper end of CO_2 concentrations and used a flexible model to link them to performance. But small and noisy effects in observational data can be misleading, especially without clear controls for confounding factors like fatigue or time of day. The supposed impact—one fewer correct answer on a multi-trial task—is tiny, and likely meaningless in the real-world. So, while the research question might be valid, the study doesn't offer strong evidence that CO_2 harms cognition.

A final example of an erroneous causal claims is the use of total volatile organic compound (TVOC) as a health metric. It is uncorrelated with any negative health effect in people. This could be explained by the harm analyses in homes and offices (Morantes et al., 2024), which show that HCHO is the most important VOC in buildings, and others can largely be ignored by standards.

When Correlation Becomes Causation

Built environment research frequently slips into causal language when associations are observed. The problem is not just with motives or funding sources, but with the methods themselves. Selection bias, publication bias, and weak statistical controls distort the narrative. Without the pre-registration of studies or formal quality assessment tools like GRADE or ROBINS-I, it becomes difficult to separate real effects from artefacts (Guyatt 2008; Sterne 2016).

Evidence of long-term effects on academic attainment is especially thin. Most studies cover short time frames and fail to track outcomes beyond immediate test scores. The lack of randomised trials (where people are randomly assigned to different groups to fairly test the effects of a treatment or intervention) or high-quality quasi-experiments (the testing of an intervention without random assignment but with a careful design to make the comparison groups as similar as possible) means the field is still guessing. As a result, it is possible to cherry-pick findings that support almost any conclusion. Cherry picking creates a false sense of certainty and leads to overconfident policy recommendations.

The most egregious example of this was a study of Italian-schools that claimed to show that increasing ventilation through mechanical ventilation reduces SARS-CoV-2 airborne transmission by over 80%, but the ventilation rates for naturally ventilated schools were all assumed to be 0.5 ACH and not measured, a likely huge underestimation of actual flow rates (Buonanno 2022). Many other confounders such as geographical location were not considered (Madhusudanan 2023).

Reducing the transmission of pathogens that cause acute respiratory infections (ARI), such as SARS-CoV-2, in schools is challenging. There are several reasons for this. Dr Mildred Weeks, in early studies on upper-room UV, warned that these interventions were unlikely to reduce ARI transmission at the community level. This was, she argued, "because of the short incubation period believed to be characteristic of such illnesses, the multiplicity of exposure in and out of the school, and the confusion of the patterns of spread by the inclusion of adults in the population at risk." Despite these reservations, the Millbank Memorial Fund funded trials of upper-room UV in schools. As predicted, the studies found no reduction in the incidence of ARI (Downes, 1950).

Other factors also limit the effectiveness of ventilation and air cleaning. Close-range transmission dominates in many settings, where air cleaning and ventilation do little to reduce dose. Over time, population immunity also shrinks the susceptible pool. Moreover, emission rates of pathogens vary dramatically between individuals — by as much as six orders of magnitude. When emission rates are low, the concentration of pathogen in room air is already very low, even in unventilated spaces (Jones 2024).

However, in naïve populations, equivalent ventilation may have some role in slowing the spread of infection. Perkins et al. (1947) observed slower spread of measles in classrooms with upper-room UV, though the total number of cases across the school remained similar to the control.

Reviewing literature

A gold-standard literature review, like those published by the Cochrane Collaboration, is a systematic review that follows strict, transparent methods to gather and assess all the best available research on a specific question. It starts with a clearly defined question and uses comprehensive search strategies to find every relevant study, not just the most convenient or well-known ones. Reviewers assess the quality of each study using standard criteria, often focusing on randomised trials. They then summarise the results, sometimes using meta-analysis to combine findings statistically. Every step is carefully documented to reduce bias, so the review is repeatable and the conclusions as reliable as possible.

The 2023 Royal Society's systematic review of the effectiveness of non-pharmaceutical interventions against the transmission mission of SARS-CoV-2 found that the evidence suggests that ventilation, air cleaning, and reduced room occupancy may help reduce transmission in some settings, but the supporting studies were generally of low quality (they were assessed to have a *critical* risk of bias in at least one area), so confidence in this conclusion is also low (Madhusudanan 2023). Whereas the 2022 Lancet COVID Commission was not a systematic review, but an *expert consensus report* informed by a targeted literature review (Sachs 2022). This means that it cannot claim to be an unbiased or comprehensive synthesis of the evidence and should be considered as expert guidance informed by selected studies, not as a definitive evidence summary. This is probably why it based its recommended airflow rates on the confounded Italian Schools study mentioned earlier.

Better Evidence Please

In medicine and public health, strong claims require strong evidence. Randomised controlled trials (RCTs) sit at the top of evidence hierarchies, followed by cluster trials, quasi-experiments, cohort studies, and cross-sectional surveys. Each has a place, but they differ in how confidently they can support cause-and-effect claims. In building science, these hierarchies are rarely applied. Instead, we rely heavily on observational data and post-hoc analysis, sometimes with minimal transparency about methods or assumptions.

Tools like GRADE and ROBINS-I help rate the quality of evidence and assess the risk of bias. They are standard in clinical research but seldom used when evaluating environmental interventions in schools. Applying them here would expose the uncertainty behind many IAQ–performance studies and help guide decisions toward more credible findings.

Until better trials are conducted, we should be cautious about promoting increased ventilation and air cleaning as mechanisms to improve academic performance and well-being. Meeting statutory ventilation standards is a sensible baseline. But going further — particularly when it involves capital investment, energy use, and disruption — should be justified by more than suggestive data.

What Should Be Done?

Beyond meeting current standards, the case for further improvement on academic grounds is weak. The pollutants most likely to affect health and learning, such as formaldehyde, $PM_{2.5}$, HCHO, NO_2, and O_3, are well known from studies in homes and offices. These should be the focus of our attention. Here, ASHRAE is leading the way (Jones, 2023), its committee on Ventilation and Acceptable Indoor Air Quality in Residential Buildings (62.2) has produced an addendum that would add a harm-based IAQ procedure as an alternative compliance method (Jones 2023). The procedure is harm-based rather than based on individual contaminant limits. The 62.2 committee has used the harm analysis in homes to determine that its IAQ Procedure needs to consider only 3 contaminants, and only the sum of the harm from those three contaminants needs to be limited. The concept has broad implications and should be considered for school.

But the assumption that marginal improvements in ventilation will meaningfully boost cognition or attainment is not supported by strong evidence. We should study the effects of ventilation on academic attainment and behaviour properly. The cost-benefits should be compared against other interventions, like giving children breakfast, improving teacher quality, reducing class sizes, and increasing physical activity.

Conclusion: Better Trials, Not Bigger Fans

The drive to improve IAQ in schools is well intentioned. It reflects a desire to protect children and promote learning, which are goals we share. But we must distinguish between what feels intuitively right and what is scientifically supported. The belief that ventilation boosts academic performance is not backed by strong, consistent, or causal evidence. Where studies do exist, they are often thin on rigour and thick with noise.

Schools should meet existing ventilation standards. That is a reasonable and defensible position. But claims that more air will improve cognition, behaviour, or test scores need better support. Overstating these effects risks misdirecting public funds and eroding trust in our industry when expected gains do not materialise.

In a world of limited budgets, we must be honest about trade-offs. Every intervention comes with capital, operational, and environmental costs. When those costs are weighed against uncertain benefits, we owe it to schools and students to demand better evidence. That means fewer headlines and more high-quality trials. Until then, we should focus on what we know works.

References

Please see the list of references in the html-version of the article at rehva.eu –> REHVA Journal ■

Evaluating the Impact of Portable Air Purifiers on $PM_{2.5}$ Reduction and Health Outcomes in Nurseries

Keywords: air purifiers, health, nursery, particle matters, $PM_{2.5}$

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Beyond their homes, children spend most of their time in schools, making it crucial to ensure good air quality in these environments. Compared to other educational settings, nurseries often report poorer indoor air quality (IAQ), which poses significant health risks to young children. Poor IAQ in nurseries can lead to respiratory issues, allergies, and developmental problems in children, thus necessitating a comprehensive understanding and improvement of IAQ in these settings. This study involved air quality monitoring in three London nurseries over 8-12 months. Indoor and outdoor pollutants were measured using both direct reading and passive monitoring methods. The mean reduction rate of $PM_{2.5}$ with air purifiers was 63% with windows closed and 46% with windows open. The QALY gain was calculated at 292.8 per 10,000 children, with potential monetary benefits from air purifier use in all UK nurseries reaching £435.9 million annually. This article provides evidence for policymakers, strongly supporting the implementation and proper operation of HEPA filter air purifiers in schools to protect the health of vulnerable children.

Introduction

Children, especially those under six years old, are more vulnerable than adults to environmental pollutants because their immune and respiratory systems are not fully developed. Outside of the home, schools are where children spend most of their time (averaging 7-11 hours per weekday in classrooms) [1]. Poor indoor air quality has negative effects on human health and performance related to respiratory illnesses, allergies, and sick building syndrome symptoms (SBS). Exposure to air pollutants before the age of one year may contribute to the development of childhood asthma. It was estimated that the United Kingdom had a population of approximately 3.58 million children aged between 0 and 4 years. Additionally, around 1.2 million children aged 3 and 4 were registered for the 15-hour entitlement program (government-funded early years provision) in UK nurseries (national statistics, UK).

Studies about indoor air quality in nurseries are scarce, and poor indoor air quality is consistently reported in nursery settings. In nurseries, $PM_{2.5}$ could be high and often exceeds the recommended level [2]. Previous studies reported mean indoor $PM_{2.5}$ levels between 19.7 to 69.5 µg/m³ [3–6]. $PM_{2.5}$ and smaller particles could easily penetrate the lungs and deposit in the respiratory bronchioles and the alveoli where gas exchange occurs. Particulate matter is one of the key risk factors for asthma. Asthma is a serious public health problem around the world. The global prevalence, morbidity and mortality related to childhood asthma among children has increased significantly over the last 40 years. The financial burden of asthma is relatively high with developed countries spending 1 to 2% of their healthcare budget on this condition [7]. In England, the national health service (NHS) notes that "the UK is one of the highest prevalence, emergency admission and death rates for childhood asthma in Europe, with around 1 in 11 children and young people living with asthma".

Air cleaning technologies have been developed and studied to mitigate the indoor pollutant level, and HEPA filtration is recommended for its high efficiency at removing PMs without producing side products (e.g. O_3, NOx). Previous studies have explored the health benefits of air purifiers in home environments for children, noting reduced asthma and nasal symptoms [8–10]. Yet, a recent review highlighted a lack of health research for younger children in schools and nurseries. More in-depth, context-specific studies are therefore essential to evaluate the effectiveness of interventions and to support policy-makers in developing evidence-based guidelines for IAQ management in educational settings [11].

Methods

In May 2018, the Mayor's Nurseries Air Quality Audits was launched to help improve the indoor air quality in nurseries in London. The work presented here was conducted as a part of the GLA's nursery study. Based on the estimated ambient annual NO_2, PM_{10} and $PM_{2.5}$ concentrations reported by London Atmospheric Emissions Inventory, as well as other relevant datasets published by GLA, 15 nurseries in London with high exposure risks were contacted and 3 of them agreed to participant this study. Indoor and outdoor concentration data of $PM_{2.5}$ was collected consistently for a 9 to 12 month period using direct reading instrument methods (Eltek TU1082-AQ110/112), data were collected at 5 min intervals and sent/stored to an online server.

Six air purifiers were installed in three nurseries, with three air purifiers in staffrooms and three air purifiers in classrooms. To check the purifier's operation, an optical pulse meter was positioned over the purifier's LED indicator, which flashes to signal that the equipment is turned on. Supplementary measurements of window status were also conducted.

Health impact assessments (HIA) were conducted focusing on the reduction of $PM_{2.5}$ and its relation to childhood asthma, with calculations of QALY gains per child. The QALY is extensively employed in health economics as a comprehensive indicator of health outcomes, aiding in decisions about the allocation of healthcare resources. The calculation of QALYs involves multiplying the length of time in a specific health state by the utility weight assigned to that state. This measure has been frequently applied in some studies evaluating the health and economic impacts of asthma. The measured $PM_{2.5}$ concentrations before and after the use of air purifiers were directly used in the HIA. In addition, the average indoor/outdoor (I/O) $PM_{2.5}$ ratio derived from this study was applied to simulate indoor exposure scenarios, allowing the potential health benefits of air purifiers to be assessed at a broader scale (London and UK). Based on the population of nursery-aged children in the UK/London and the monetary value assigned to one QALY, along with the costs associated with air purifiers (both purchase and operational costs) for the assumed population, the monetary benefits could be evaluated.

Results

Indoor $PM_{2.5}$ levels across different seasons

Figure 1 displays the recorded levels of $PM_{2.5}$ both indoors and outdoors over two seasons. The median indoor $PM_{2.5}$ levels in this study ranged between 0.3 and 6.1 μg/m³ during occupied hours (rooms with purifiers had median concentrations between 0.3 and 2.5 μg/m³, and rooms without air purifiers had median concentrations between 3.3 and 6.1 μg/m³). In most studied rooms, median concentrations were under the 5 μg/m³ (annual average exposure) recommended by WHO. However, in the seven classrooms without air purifier, only 54% of total occupied hours were below 5 μg/m³ across the study. For all rooms with air purifiers, the total occupied hours below 5 μg/m³ was as much as 88%.

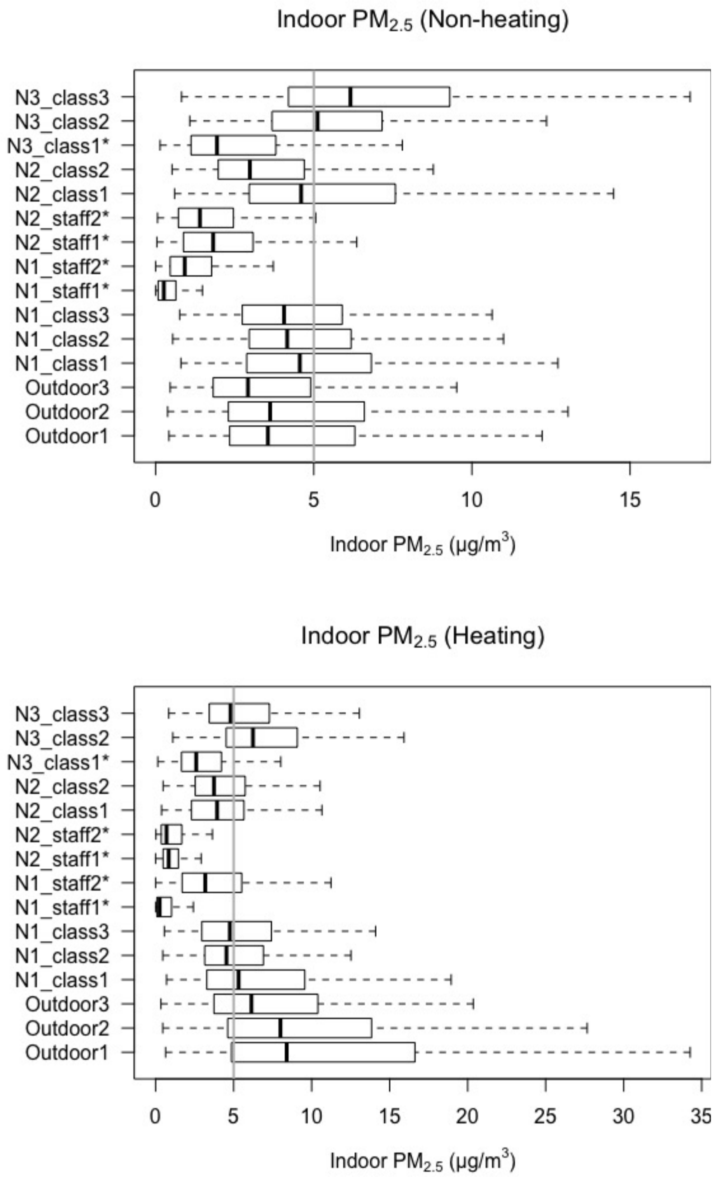

Figure 1. Indoor and outdoor PM2.5 levels across different seasons (greyline indicates maximum indoor level recommended by WHO; *represents rooms with air purifiers).

Impact of air purifier on IAQ

Normal nursery settings

Figure 2 illustrates the differences of $PM_{2.5}$ concentrations in studied rooms when air purifiers were either off or on (occupied hours and working days only). Even in staffrooms, which tended to have lower PM levels than classrooms, the reductions are clear. It is worth noting that when the air purifiers were turned off, the mean $PM_{2.5}$ concentrations in two classrooms were 6.6 μg/m³ and 7.3 μg/m³, which were higher than the WHO guideline of 5 μg/m³ (annual mean). However, the air purifiers lowered the $PM_{2.5}$ concentrations below the recommended level (3.4 μg/m³ and 2.3 μg/m³) in those classrooms (mean reduction in classrooms: 4.1 μg/m³).

Severe polluted settings

Figure 3 shows a special scenario when a nursery had been closed during summer vacation and some construction works were conducted in two classrooms which generated a lot of PMs (the work ended around 3 pm). The data were collected after the workers left, and rooms were unoccupied with all the windows and doors closed. The two rooms were next to each other, room 1 without an air purifier and room 2 with the air purifier on. Even with a high initial PM concentration, the $PM_{2.5}$ level dropped close to 0 from the peak (165.2 μg/m³) within 45 minutes in room 2. However, in room 1without air purifier, the $PM_{2.5}$ level dropped from 112.5 μg/m³ to 41.7 μg/m³, then dropped to 8 μg/m³ after 5 hours.

Impact of air purifier and window operation on IAQ

Figure 4 shows the indoor $PM_{2.5}$ decay curves during the period of air purifier operation when opening and closing windows. Note, as purifiers typically started 1 hours before opening hours, peaks, likely associated with resuspension following the children's arrival (around 9:00 a.m.), can often be seen around 60 mins after the purifier started operating. The plot aggregated the data during whole operation period of air purifier (around 200 working days), which includes different outdoor conditions and indoor activities.

Evaluation of indoor $PM_{2.5}$ exposure in London/UK Settings

The monitored mean indoor $PM_{2.5}$ level in three nurseries was 8.3 μg/m³ in 2021. Without air purifiers in operation, the mean level was 7.0 μg/m³; and with air purifiers in operation, the mean level was 2.9 μg/m³ in the studied rooms. For subsequent indoor exposure simulations, two different ambient outdoor levels were employed for UK and London. The annual mean concentration of $PM_{2.5}$ in the UK was 8.3 μg/m³ in 2022 (data from LAEI). In addition, as calculated from the pollutant map of LAEI, the mean outdoor $PM_{2.5}$ level of London nurseries was 9.8 μg/m³. Thus, simulated

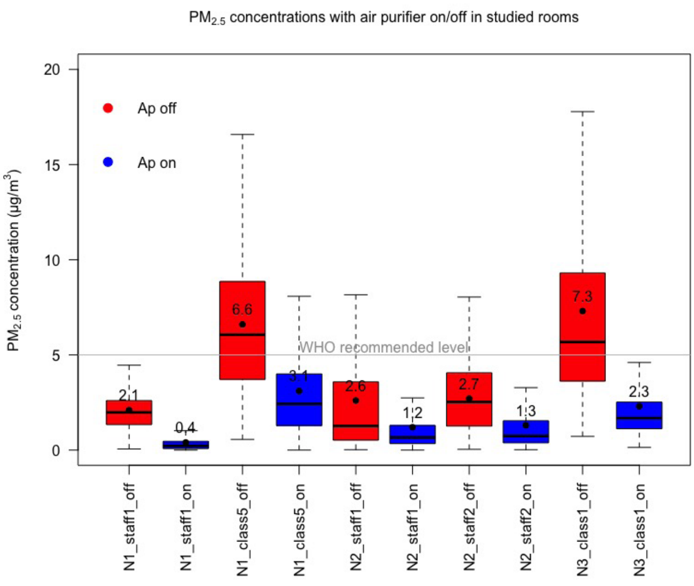

Figure 2. $PM_{2.5}$ concentrations in rooms with air purifiers; red boxes are when air purifiers were turned off; blues boxes are when air purifiers were turned on; the air flow rate of the air purifier selected is 820 m³/h, and the ideal ACH (air change per hour) for air purifier was kept around 3-4 in all studied rooms; N1_class5 represents N1_staff2 (it was used as classroom in heating season and staffroom in non-heating season).

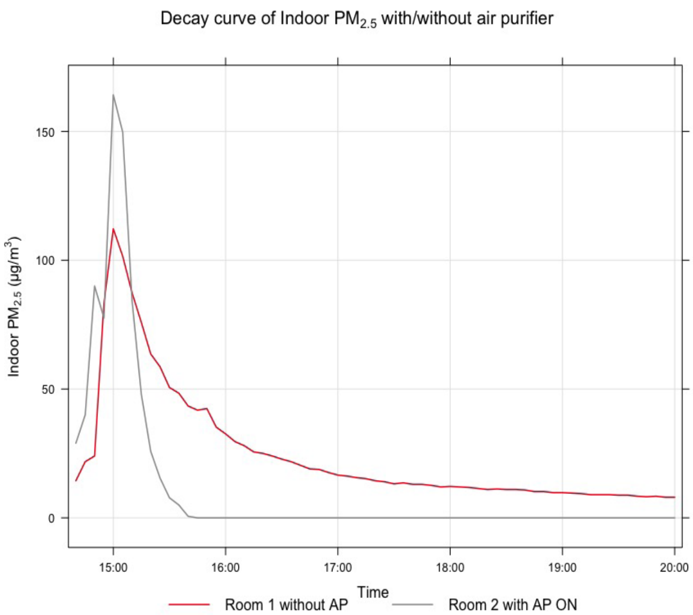

Figure 3. The decay curve of indoor $PM_{2.5}$ with and without air purifier (a special scenario when nursery was unoccupied but with high PM levels). Room 1 without air purifier; room 2 with air purifier on for the whole period.

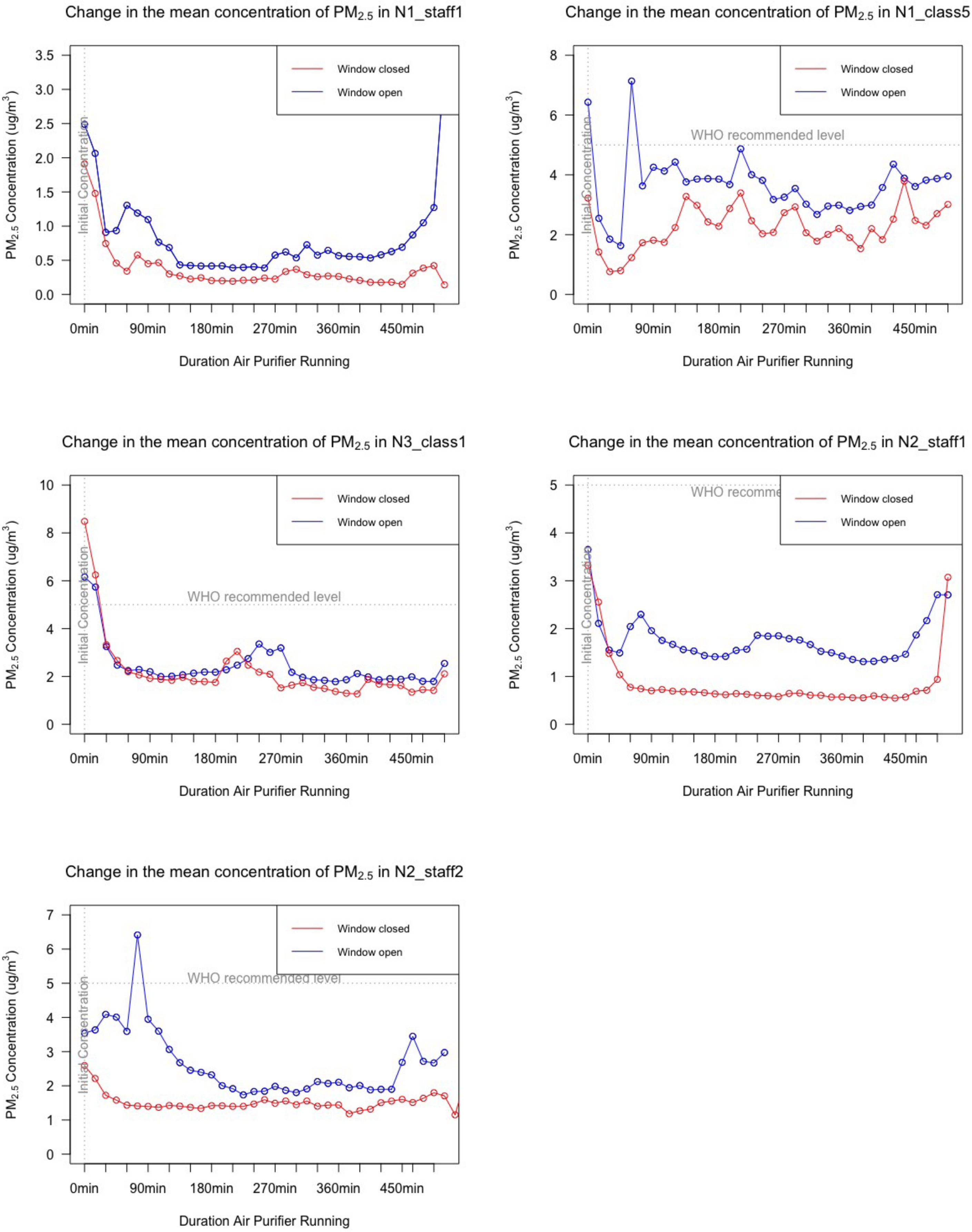

Figure 4. Change in the mean concentration of $PM_{2.5}$ in rooms with air purifiers.

indoor $PM_{2.5}$ levels were calculated based on the predicted mean outdoor level and are listed in **Table 1**.

Quantification of health impact

QALY gains based on monitored and simulated data

As shown in **Table 2**, using appropriately sized and well-functioning air purifiers in the nursery was estimated to save 200.7 QALYs per 10,000 children per year from childhood asthma in 2021.

Different QALY gains u in London/UK nursery settings were calculated and shown in **Table 3**. For nurseries in London, the QALY gain was 360.7 per 10,000 children. For the UK national nursery children population, the QALY gain was 292.8 per 10,000 children.

Monetary benefit of QALY gains

Total monetary benefit of reducing $PM_{2.5}$ concentrations in UK nurseries is listed in **Table 4**. The QALY loss equivalent for health care cost (cost of using air purifier) was 2280.4 QALYs and 15.2 QALYs for UK and London (local authority nurseries), respectively. In England, the net QALY gain was 33,791 QALYs for nursery children using air purifiers, with monetary benefits of £435.9 million. For nurseries in London, the net QALY gain was 7,740 QALYs, with monetary benefits of £99.8 million. This amount could be higher if children spend more time in nursery or assuming a higher cost-per-QALY.

Discussion

The impact of air purifiers on IAQ

Although the median $PM_{2.5}$ levels in most studied classrooms were lower than the guideline of 5 μg/m³ (the annual average exposure) suggested by WHO, in the classrooms without air purifier, only 54% of total occupied hours fulfilled the WHO guideline (in rooms with air purifier, the percentage could reach 89%). In this study, the deployment of air purifiers in classrooms led to a mean $PM_{2.5}$ reduction of 4.1 μg/m³. The performance of the air purifier might be affected by the operation of windows and the level of outdoor air pollution. When evaluating the performance of the air purifier, season and region factors should be considered, as there may be variations in window operation and outdoor pollution levels.

Table 2. *Health impact calculations by harm class and air purifier use.*

HIA calculation (for 10,000 children spending 7 hours/day[1] in filtered classroom)			
Exposure - $PM_{2.5}$ (μg/m³)			
Outdoor level	8.3	Pre-intervention	7.0
		Post-intervention	2.9
Impact (QALYs)			
Harm class	Pre-intervention	Post-intervention	Impact (pre-post)
I	-	-	-
II	535.1	437.6	97.5
III	247.4	185.9	61.5
IV	218.1	176.4	41.7
Total	1,000.5	799.9	**200.7**

1. Nursery opened to children 7 hours a day and 38 weeks a year in the UK.

Table 3. *QALY gains in London/UK nursery settings.*

London (Outdoor $PM_{2.5}$ = 9.8 μg/m³)	
Pre-intervention (μg/m³)	9.5
Post-intervention (μg/m³)	2.6
QALY gain (per 10,000 children)	**360.7**
UK (Outdoor $PM_{2.5}$ = 8.3 μg/m³)	
Pre-intervention	8.1
Post-intervention	2.2
QALY gain (per 10,000 children)	**292.8**

Table 1. *Annual mean I/O ratios under different scenarios it's indoor $PM_{2.5}$ exposure.*

Scenario	Setting	I/O Ratio (mean)	UK	London
			$PM_{2.5}$ exposure[1]	$PM_{2.5}$ exposure[2]
Outdoor	-	-	8.3	9.8
Pre-intervention	Occupied hours, without air purifier	0.97	8.1	9.5
Post-intervention	Occupied hours, air purifier On	0.26	2.2	2.6

1. Evaluated indoor levels in 2022; unit: μg/m³.
2. Evaluated indoor levels in 2025; unit: μg/m³.

Health and monetary benefits of using air purifiers

Air purifier could be used indoors for children with asthma. The asthma costs per patient per year (including all asthmatics: intermittent, mild, moderate, and severe asthma) in Europe was $1,900 (approximate £1,532) [12], and around 160,000 patients (reported by British Lung Foundation) received an asthma diagnosis each year. Thus, the financial burden would be around £245 million a year related to asthma in the UK. In this study, the costs of air purifier were £29.4 million per year, and it could potentially bring £435.9 million monetary benefits. Although £29.4 million per year is not a small budget, compared with financial burden and monetary benefit, it seems like reasonable to use air purifier indoor, especially for vulnerable group. For stakeholder and government, promoting the use of air purifiers in schools or homes is highly recommended. In most cases, the health benefits and savings outweigh the initial investment required for using air purifiers.

Conclusion

Impact of air purifiers and window operations on IAQ

- Air purifiers were effective at reducing mean $PM_{2.5}$ levels by 46% (with at least one window open) and 63% (with windows closed), increasing the total occupied hours with $PM_{2.5}$ below 5 μg/m³ to 88%. This level of IAQ improvement could substantially reduce exposure of $PM_{2.5}$ to children in nursery care even with significant natural ventilation.
- When assessing air purifier performance, it's crucial to consider several specific factors separately: the state of windows (as indicators of ventilation), the level of outdoor pollution, and the background of seasonal and regional variations. Each element could impact air quality: window states influence indoor pollutant levels, outdoor pollution sets the baseline air quality, and seasonal/regional factors affect window behaviours.

Health and monetary benefits of using air purifiers

- The results suggested that by applying air purifiers in nurseries across the UK, a substantial QALY gain of 292.8 per 10,000 children in the UK (360.7 per 10,000 children in London) can be achieved.
- With the cost of £29.4 million per year for installing and operating air purifiers in UK nurseries, the potential monetary benefits could range from of £435.9 million. These findings strongly advocate for the widespread adoption of air purifiers in schools, particularly for the well-being of vulnerable children.

References

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Table 4. *Total monetary benefit of reducing $PM_{2.5}$ concentrations in UK nurseries.*

	UK	London	Authority Funded Nurseries[4]
Target population	1,231,925[1]	226,197	8,163
QALY gain	36,071	8,159	164
QALY Value[2]	£12,900	£12,900	£12,900
Net health care costs (per year)[3]	**£29,416,702**	**£5,401,877**	**£195,486**
Unit number	37,319	6,853	248
Air purifier cost	£27,989,250	£5,139,750	£186,000
Utility Cost	£1,427,452	£262,127	£9,486
QALY loss equivalent	**2,280**	**419**	**15**
Net QALY gain	**33,791**	**7,740**	**149**
Total monetary benefit	**£435.9 million**	**£99.8 million**	**£1.9 million**

1. Equivalent population of registered nursery children in 2021
2. £12,900/QALY was applied based on NHS cost
3. The health care cost was mainly about air purifier related costs (the initial investment in the unit, utility and filter cost)
4. Local authority nurseries in London (77 in total)

Direct impact of short-term exposure to pure carbon dioxide levels on cognitive performance

Keywords: cognitive performance, carbon dioxide, students, environmental chamber

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Abstract

To generate further evidence on the effects of pure CO_2 on cognitive performance, an experiment was conducted in an environmentally controlled chamber. Sixty-nine healthy university students were exposed individually for seventy minutes, in three separate sessions, to three CO_2 conditions of 600, 1500 and 2100 ppm (crossover design). A validated neurobehavioral BARS test battery was used to assess participants' cognitive performance. Results indicated that the cognitive performance of university students, measured by the BARS test battery, was not adversely affected by pure CO_2 below 2100 ppm. The findings are consistent with some prior studies, indicating that pure CO_2 within the guideline range does not imply any harm and could be treated primarily as a proxy for ventilation rates and indoor air quality in the indoor environments.

Introduction

Human exposure to indoor carbon dioxide has increased over the years due to climate change, given the growth in atmospheric CO_2 concentration [1], whilst, on the other hand, ventilation rates have been drastically reduced for energy-saving reasons [2]. Raised concerns about the impacts of elevated CO_2 concentrations on performance in the educational environment have drawn lots of attention, as schools normally face the problems of increased occupancies and decreased ventilation rates. In the UK, the Department for Education and Skills provides a guidance standard document Building Bulletin 101 (BB101) for educational buildings [3], which recommends an average concentration of CO_2 should not exceed 1500 ppm and 2100 ppm with a minimum ventilation rate of 3L/s-p. Average levels of CO_2 concentrations normally range from 600 to 1000 ppm in the educational environment, sometimes may surpass 2000 ppm and even reach a peak level of 4000 ppm [4], [5]. Cognitive performance and learning outcomes [6]–[8] showed decrements with inadequate air quality (characterized by CO_2 levels) in schools. In these studies, poor air quality due to insufficient ventilation rates might cause impairment in performance, and CO_2 was seen as a proxy for ventilation rates but not a potential pollutant. Nonetheless, adjusting ventilation rates during the experiment would affect the concentrations of other indoor pollutants like bioeffluents and contribute to cognitive performance decrement.

However, rather than being a proxy of ventilation effectiveness and an indicator of air quality, carbon dioxide itself started to gain attention in a limited number of studies about its direct impact on humans in the indoor environment. Regarding the results of cognitive performance under elevated pure CO_2 levels in previous studies (**Table 1**), the findings were inconsistent. Significant adverse effects of pure CO_2 on cognitive performance have been reported by some lab studies [9]–[16], and cognitive performance such as decision-making [9], [10] have been found at levels as low as 1000 ppm in the chamber and laboratory, while other studies found no statistically significant effects on cognitive performance during exposures [17]–[21]. The conflicting outcomes between the studies may be due to the diverse cognitive tests used in the experiment, differences in study populations, and disparity in the experimental procedure. The inconsistent results from previous studies and the potential socioeconomic impact due to cognitive performance decrements in built environment stimulated this research project, conducted in an environmentally controlled chamber, to generate further evidence on the effects of pure CO_2 on cognitive performance, using a systematically structured valid test battery.

Table 1. Summary of previous studies exploring the effects of pure CO_2 on cognitive performance in built environment.

Study	CO_2 levels (ppm)	Ventilation rates	Subjects [a]	Environment	Time (h)	Cognitive Task	Effects of elevated CO_2	Response speed [b]	Accuracy [c]
Kajtar et al., 2012 [12]	E1: 600, 1500, 2500, 5000 E2: 600, 1500, 3000, 4000	33.3 L/s	Unknown occupations (E1: 10; E2: 10)	Laboratory room	E1: 2.33 E2: 3.5	Proofreading	E1: No effect E2: Reduced proofreading performance	No effect	600 vs 4000* (-)
Satish et al., 2012 [9]	600, 1000, 2500	24.85 L/s-p	University students (22)	Chamber	2.5	SMS	Reduced decision-making performance		
Allen et al., 2016 [10]	500, 1000, 1400	18.6 L/s-p	Office workers (24)	Lab with office environment	6.75	SMS	Reduced decision-making performance		
Zhang et al., 2016 [19]	500, 5000	33.3 L/s-p	University students (10)	Chamber	2.5	Text typing + Addition + Tsai-Partington	No effect	No effect	No effect
Liu et al., 2017 [20]	400, 3000	66.7 L/s-p	University students (12)	Chamber	3	Multiple tasks	No effect	No effect	No effect
Zhang et al., 2017 [18]	500, 1000, 3000,	33.3 L/s-p	University students (25)	Chamber	4.25	Multiple tasks	No effect	No effect	No effect
Allen et al., 2019 [11]	700, 1500, 2500	850 L/s	Pilots (30)	Flight simulator	3	FAA PTS	Reduced pilot performance as assessed by the examiner		
Snow et al., 2019 [21]	830, 2700	Background infiltration	University students (31)	Office room	1.97	CNS Vital signs battery	No effect	No effect	
Zhang et al., 2020 [13]	1500, 3500, 5000	8.68 L/s-p	University students (15)	Chamber	2	MATB	Reduced MATB task performance (system mentoring, tracking, scheduling and resource management)	MATB: 1500 vs 3500* (-)	
Pang et al., 2021 [14]	1500, 3500, 5000	8.68 L/s-p	University students (15)	Chamber	4	PVT+ Cognitive tasks	Reduced vigilance	PVT: 1500 vs 5000* (-)	PVT: 1500 vs 3500* (-)
Tu et al., 2021 [16]	8000, 10 000, 12 000	0.5 L/s (Air purifier) + 0.052 L/s (O_2)	University students (30)	Chamber	4	Text typing + Numerical calculation	Reduced text typing performance	Text typing: 8000 vs 12000* (-)	No effect
Maniscalco et al., 2021 [17]	770, 20 000	94.4 L/s	Workers (24)	Chamber	4	TAP	No effect	No effect	No effect
Cao et al., 2022 [15]	1500, 3500, 5000	8.68 L/s-p	University students (15)	Chamber	1.67	Multiple tasks	Reduced performance of visual attention, risky decision-making, and executive ability	VS, BART, Stroop: 1500 vs 5000* (-)	No effect

[a] The number in the bracket shows the sample size of the whole experiment or specific session; [b] Effects of exposures to CO_2 on response speed, * means significant difference between the two exposure levels, (+) means response speed increased at higher CO_2 levels, (-) means response speed decreased at higher CO_2 levels; [c] Effects of exposures to CO_2 on the accuracy, * means significant difference between the two exposure levels, (+) means accuracy increased at higher CO_2 levels, (-) means accuracy decreased at higher CO_2 levels)

Methods

Facilities

The experiment was conducted in a stainless-steel environmentally controlled chamber (**Figure 1**), measuring 4.4m wide × 4.6m deep × 3.0m high inside, with an internal volume of approximately 60m³. Through the chamber controller (**Figure 2**), the researcher accomplished precise control of the chamber environment, achieving defined temperature, humidity, CO_2 concentration levels and ventilation rates. Outdoor air was drawn through a HEPA filter from the building ventilation system and expelled into the chamber through a diffuser. Chemically pure carbon dioxide (99.8%) was automatically drawn from a cylinder and well mixed with outdoor air to reach the desired test levels in the chamber.

Figure 1. Image of the chamber and experiment setup.

Figure 2. The screen of the Watlow F4T Controller outside the chamber.

Experimental procedure

Sixty-nine participants were recruited from university students, including thirty-seven females and thirty-two males. Participants visited the environmentally controlled chamber at UCL Here East three times, each time exposed alone to one CO_2 condition and lasted 70 minutes (**Figure 3**). The interval between two experiment sessions was at least four weeks, to minimise the learning effects of cognitive tests. Participants were advised to ensure adequate sleep, avoid intense physical activity for at least 12 hours prior to the experiment, avoid drinks and non-essential medications containing caffeine and refrain from strong-scent perfume. Under a fixed high ventilation rate of 108m³/h, CO_2 was reduced to the background levels at the baseline condition, and higher CO_2 conditions were achieved with injection of pure CO_2. The temperature (23°C) and relative humidity (50%) were kept constant in all three conditions. The participant first gave written and informed consent to the participation, then was suggested to do some quiet non-work-related activities to adapt to the chamber environment, for about 20 minutes. When the time was up, the participant put on the noise-cancelling headphones and started the BARS test on the laptop, lasting about 40 minutes. After the cognitive test, the participant filled in a post-assessment questionnaire at the end of the experiment.

BARS test battery

As a computerised assessment system designed to evaluate the neurobehavioral function of individuals, the BARS test battery [22] has been mainly used to study the effects of chemical exposure on performance [23], [24]. In this study, ten tests (**Table 2**) were selected to assess participants' cognitive performance during exposure to different CO_2 concentration levels: match to sample, continuous performance test, symbol digit test, tapping, simple reaction test, reversal learning test, selective attention test, digit span, serial digit learning and progressive ratio test.

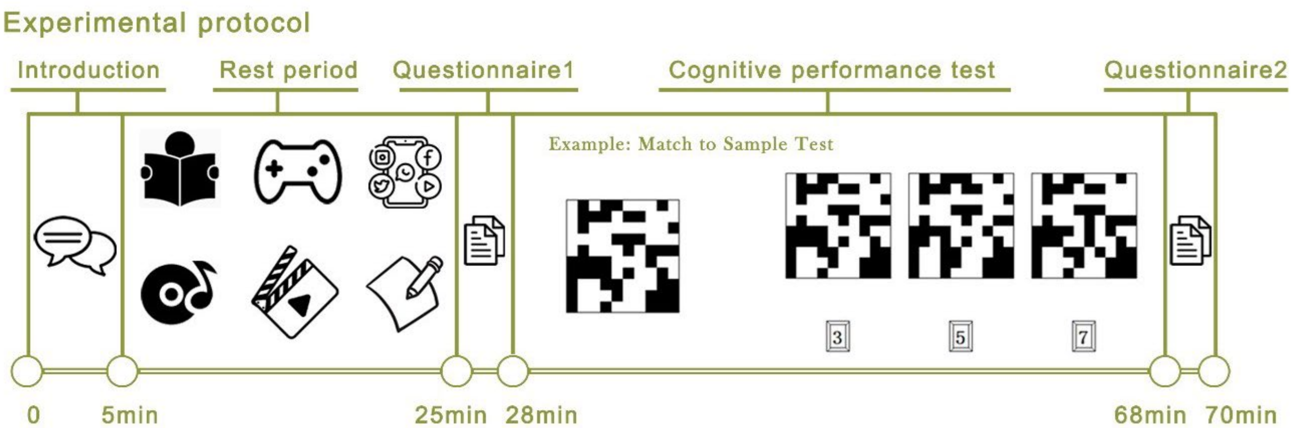


Figure 3. Diagram of the experimental protocol.

Results

Measured conditions of the chamber environment

Table 3 presents the conditions measured in the environmental chamber during exposures. The average CO_2 concentration levels in the baseline, intermediate and high conditions were 633, 1520 and 2120 ppm, described as 600, 1500 and 2100 ppm in the paper. The results showed that CO_2 levels were effectively controlled within 64 ppm of the desired exposure levels in all conditions.

Cognitive test results

Due to the repeated measurements, univariable linear mixed-effect models were used to assess the association between cognitive test results (response times and error rates) and CO_2 concentrations. Factors that were significantly associated with at least five cognitive performance outcomes across the three conditions were then included in multivariable mixed-effect models to correct for confounding. After adjusting for potential confounders, only a few of the cognitive performance outcomes demonstrated significant effects (**Table 4**). Regarding response times, only two found statistically significant decreases (**Figure 4**). For the Selective Attention test and the Progressive Ratio Test, the response times significantly decreased at 1500 ppm and 2100 ppm, compared to the baseline condition. Regarding the error rates of cognitive tasks, no significant effect on accuracy was found in any of the ten BARS tests.

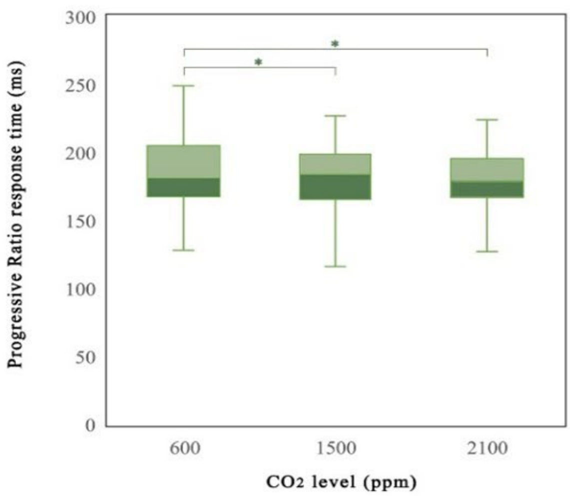
Table 2. *Cognitive domains tested in the BARS battery.*

Neurobehavioral test	Cognitive domain
Match-to-Sample (MTS)	Visual memory capacity (working memory), learning, selective attention, visual processing
Continuous Performance Test (CPT)	Sustained visual attention (vigilance)
Symbol Digit Test (SDT)	Attention, motor speed, processing speed, working memory, visual scanning and tracking, visual learning
Tapping (TAP)	Motor speed, coordination, sustained attention
Simple Reaction Time (SRT)	Sustained attention (vigilance), motor speed
Reversal Learning Test (RLT)	Learning
Selective Attention Test (SAT)	Selective attention, coordination, inhibition control
Digit Span (DST)	Learning, attention, working memory, executive function
Serial Digit Learning (SDL)	Learning, digital memory capacity (working memory)
Progressive Ratio (PRT)	Motivation, sustained attention

* Parameters that randomly changed within a defined range each time to generate parallel tests

Table 3. *Measured conditions in the environmental chamber (mean ± standard deviation)*

Condition	CO_2 (ppm)	Temperature (°C)	RH (%)	Ventilation rates (m^3/h)	TVOC ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	PM Total ($\mu g/m^3$)
1	633 ± 64	23.2 ± 0.1	50 ± 1	108.1 ± 0.4	110 ± 99	0.2 ± 0.6	0.2 ± 0.6	0.4 ± 0.7
2	1520 ± 27	23.2 ± 0.1	50 ± 1	108.0 ± 0.2	116 ± 105	0.2 ± 0.5	0.2 ± 0.5	0.3 ± 0.6
3	2120 ± 36	23.2 ± 0.1	50 ± 1	107.9 ± 0.3	105 ± 103	0.2 ± 0.4	0.3 ± 0.5	0.4 ± 0.6



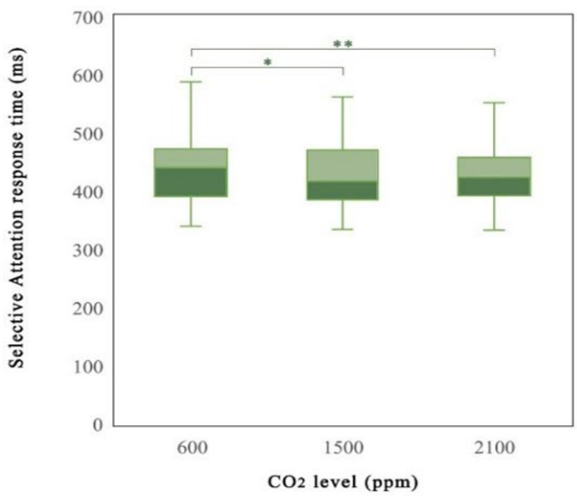


Figure 4. Response times of Progressive Ratio test and Selective Attention test at three CO_2 exposure levels of 600, 1500 and 2100 ppm. $^*p < 0.05$, $^{**}p < 0.01$.

Table 4. Univariable and multivariable associations of conditions with response times and error rates in the ten BARS tests.

CO_2 levels (ppm)	Response times of BARS tests				Error rates of BARS tests			
	Univariable models		Multivariable models*		Univariable models		Multivariable models*	
	β- coeff. (95% CI)	p-value	Adj.β- coeff. (95% CI)	p-value	β- coeff. (95% CI)	p-value	Adj.β- coeff. (95% CI)	p-value
MTS								
600	Ref.		Ref.		Ref.		Ref.	
1500	-11.06 (-190.66, 168.55)	0.90	49.48 (-126.33, 225.29)	0.58	-1.21 (-4.60, 2.18)	0.48	-1.12 (-4.46, 2.23)	0.51
2100	-36.81 (-256.81, 183.19)	0.74	28.58 (-178.88, 236.04)	0.79	-1.01 (-4.88, 2.86)	0.61	-1.22 (-4.93, 2.48)	0.52
CPT								
600	Ref.		Ref.		Ref.		Ref.	
1500	-1.58 (-11.59, 8.43)	0.76	0.92 (-8.89, 10.74)	0.85	0.41 (-0.54, 1.35)	0.40	0.03 (-0.90, 0.97)	0.94
2100	-8.58 (-21.55, 4.39)	0.19	-8.84 (-21.28, 3.59)	0.16	-0.16 (-1.23, 0.90)	0.76	-0.26 (-1.29, 0.77)	0.62
PRT								
600	Ref.		Ref.		Ref.		Ref.	
1500	-4.80 (-8.87, -0.72)	0.02	-4.14 (-8.09, -0.19)	0.04	-0.001 (-0.003, 0.001)	0.51	-0.001 (-0.003, 0.001)	0.42
2100	-6.10 (-11.54, -0.66)	0.03	-6.65 (-11.76, -1.54)	0.01	-0.001 (-0.004, 0.001)	0.26	-0.002 (-0.004, 0.001)	0.20
SDT								
600	Ref.		Ref.		Ref.		Ref.	
1500	-6.13 (-59.81, 47.55)	0.82	1.94 (-46.20, 50.07)	0.94	-0.06 (-0.98, 0.85)	0.89	-0.13 (-1.04, 0.78)	0.78
2100	2.04 (-68.37, 72.46)	0.95	23.72 (-37.38, 84.82)	0.45	0.61 (-0.39, 1.61)	0.23	0.46 (-0.50, 1.41)	0.35
SDL								
600	Ref.		Ref.		Ref.		Ref.	
1500	21.45 (-285.85, 328.75)	0.89	44.60 (-261.82, 351.03)	0.77	3.06 (-1.08, 7.20)	0.15	3.65 (-0.38, 7.68)	0.08
2100	-70.72 (-433.05, 291.60)	0.70	43.57 (-288.26, 375.40)	0.80	1.77 (-3.38, 6.93)	0.50	2.10 (-2.65, 6.86)	0.38
TAP								
600	Ref.		Ref.		Ref.		Ref.	
1500	-0.33 (-29.94, 29.27)	0.98	7.51 (-20.56, 35.58)	0.60	0.66 (-0.11, 1.44)	0.09	0.47 (-0.31, 1.25)	0.24
2100	-1.59 (-38.56, 35.37)	0.93	5.58 (-28.85, 40.01)	0.75	-0.03 (-0.87, 0.82)	0.95	-0.05 (-0.87, 0.77)	0.90
DST								
600	Ref.		Ref.		Ref.		Ref.	
1500	-134.68 (-450.27, 180.91)	0.40	-52.00 (-357.17, 253.17)	0.74	-1.49 (-3.37, 0.39)	0.12	-1.49 (-3.37, 0.38)	0.12
2100	-193.90 (-558.69, 170.89)	0.30	-75.44 (-420.06, 269.18)	0.67	-0.93 (-3.20, 1.34)	0.42	-0.55 (-2.67, 1.57)	0.61
SRT								
600	Ref.		Ref.		Ref.		Ref.	
1500	-0.65 (-19.21, 17.91)	0.95	-0.95 (-19.73, 17.84)	0.92	-0.003 (-0.019, 0.013)	0.72	-0.007 (-0.024, 0.010)	0.38
2100	-8.97 (-30.22, 12.28)	0.41	-9.16 (-29.85, 11.53)	0.38	0.005 (-0.012, 0.021)	0.58	0.004 (-0.013, 0.020)	0.66
SAT								
600	Ref.		Ref.		Ref.		Ref.	
1500	-8.88 (-18.73, 0.96)	0.08	-11.29 (-21.11, 1.47)	0.03	0.45 (-1.91, 2.81)	0.71	0.77 (-1.63, 3.19)	0.53
2100	-17.57 (-29.57, -5.56)	0.004	-17.59 (-28.90, -6.29)	0.002	-1.41 (-3.95, 1.13)	0.27	-1.41 (-4.04, 0.76)	0.18
RLT								
600	Ref.		Ref.		Ref.		Ref.	
1500	100.26 (-130.39, 330.91)	0.39	151.85 (-60.44, 364.14)	0.16	0.22 (-2.51, 2.95)	0.88	0.46 (-1.52, 2.44)	0.65
2100	6.81 (-221.50, 235.12)	0.95	68.45 (-139.16, 276.06)	0.52	1.51 (-1.74, 4.76)	0.36	1.94 (-0.40, 4.27)	0.10

* Model adjusted for gender, age, first language, weekday, test durations, time slots, perceived air quality (before BARS test), perceived noise level and perceived difficulty level.

Discussion

This study indicates that exposures to pure elevated CO_2 levels up to 2100 ppm were not associated with detrimental changes in individuals' cognitive performance in eight out of ten tests, while Selective Attention and Progressive Ratio tests reported significantly improved performance with reduced response time at 1500 and 2100 ppm, compared to a baseline of 600 ppm. Our results deviated from some previous studies that indicated detrimental effects, and were consistent with those that found no effects. Compared with most studies which found adverse effects, our study used relatively lower CO_2 levels, aiming to examine the effects at low-to-moderate levels close to routine scenarios. Some studies [12]–[14], [16] testing higher concentrations exceeding 3000 ppm tended to be more likely to exhibit the effects of CO_2 on individuals. Disparities in the results might be partly due to the different population groups. This study was consistent with the two studies which found no effects on university students [18], [20], contrary to Allen et al. which focused on office workers [10] and pilots [11]. One possible explanation for the discrepancies among the findings could be the different cognitive assessment methods employed. Allen et al. and Satish et al. both found decrement in decision-making performance with the SMS battery, which was described as a sensitive cognitive function assessment tool, but limitation also exists, as Rodeheffer et al. [25] mentioned.

Regarding the two tests which reported improved speed at higher CO_2 levels, Zhang et al. [26] found that the beta relative power of EEG significantly increased at higher concentrations, indicating that elevated CO_2 levels could be associated with higher arousal. Zhang et al. [18], [19] postulated a weak indication of arousal increased at higher CO_2 levels, based on the slightly increased $ETCO_2$ and reduced performance of Tsai-partington test. Arousal could play a crucial role in performance, but it remains unclear why some tests were affected with other tests showed no effect. Therefore, the improvement of performance measured by response times in the two tests could be due to higher arousal under higher CO_2 levels. Another explanation of the significant results of response time in two tests might be increases in alpha error due to multiple comparisons [27] of ten tests. Significant results from numerous tests sometimes could be false positives due to chance.

Conclusion

This study examined whether different pure CO_2 concentrations below 2100 ppm impact cognitive performance, independent of ventilation rates. With only two out of ten tests showing significant increases in response times and no significant results in accuracy under higher CO_2 levels, the findings provide empirical evidence that the cognitive performance of university students, measured by the BARS test battery, was not adversely affected by pure CO_2 below 2100 ppm, consistent with the current guidelines and some previous studies. More importantly, not only that some of the results from prior studies which reported decrements in cognitive performance could not be confirmed in this study, the contrary was found. This adds to the uncertain nature of evidence in this field, although more research is needed to confirm this finding which could be due to arousal effects or to numerous testings across several variables. The results indicate that for regulatory purposes CO_2 levels below 2100 ppm could be treated primarily as a proxy for ventilation rates and indoor air quality, while concerns still exist when levels rise above that to the occupational exposure limit of 5000 ppm.

References

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The Impacts of Indoor Total Volatile Organic Compounds on Cognitive Performance of University Students

Keywords: Cognitive performance, air quality perception, temperature, interaction, VOCs.

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In educational buildings, poor air quality can adversely affect learning and creativity. Existing evidence indicates that high Total Volatile Organic Compounds (TVOC) levels can lead to health issues and reduced cognitive performance. The rising temperatures cause more overheating in buildings. It is crucial to investigate the effects of indoor TVOC levels and temperatures on learning-related cognitive performance in university students.

This project explored the topic through two independent single-blind experiments conducted in a human climate chamber. Experimental Study 1 utilized three TVOC concentrations (100, 1000, and 2000 μg/m³) and involved 33 university students. Experimental Study 2 adopted two temperatures (23°C and 28°C) and two TVOC concentrations (100 and 1000 μg/m³), with 71 university students participating. Cognitive performance was assessed using the BARS cognitive test battery; participants provided their subjective experience of the environment via paper-based questionnaires before and after the experiment.

Result shows only accuracy performance was significantly affected under higher TVOC (2000 μg/m³) and higher temperature (28°C), respectively. The impact of these conditions on reaction speed were inconclusive. The effects of moderate TVOC levels (1000 μg/m³) on both accuracy and reaction speed were also unclear.

Background

Poor IEQ affects teachers and students, negatively impacting teaching effectiveness and students' academic performance [1]. Volatile Organic Compounds (VOCs) are common air pollutants. These compounds are released by building materials, occupants, and various equipment within a building, potentially leading to indoor air quality issues in different areas [2]. Walls and ceilings make up approximately 60% of the total indoor space and are frequently painted [3]. Paints can release amount of VOCs, especially in structures shortly after construction and renovation. Total volatile organic compounds (TVOC) refer to the combined concentrations of both identified and unidentified VOCs.

Climate change is leading to a consistent rise in average temperatures and an increasing frequency of heatwaves worldwide. Highly airtight structures can result in insufficient ventilation, leading to potential overheating and the accumulation of air pollutants [4, 5]. Many studies have highlighted instances of overheating in UK schools [6, 7]. Elevated temperatures can further increase VOC emission rates of building materials, resulting a potential risk to students exposed to both high temperatures and elevated TVOC concentrations.

According to the British standard BS EN 16798-1, a TVOC level below 300 μg/m³ is deemed very low, while a medium level of about 1000 μg/m³ is acceptable [8]. The BS EN 16798-1 also mentions the upper limit for acceptable classroom temperatures during summer as 28°C [8]. Elevating indoor temperatures may lead to productivity losses and the onset of health symptoms [9, 10]. Research on the impact of VOCs on cognitive performance remains inconclusive. Investigation into the combined effects of temperature and VOCs on cognitive performance is even less. Except one early study, no recent studies have delved into this specific area of research [11].

Experimental studies

We conducted two experimental studies to better understand university students' cognitive function and perception during acute exposure to VOCs and elevated temperatures. Both studies were conducted in a controlled, mechanically ventilated climate chamber. The ventilation rate was controlled to 8.3 L/s per person, relative humidity was maintained at 50%. A commercially available solvent-based paint was chosen as the VOC source. The TVOC levels were generated using a paint container assembled from a jar and a lid with an opening. Indoor air was analyzed by the GC-MS system. Tiger PID gas detectors were utilized to enable real-time monitoring. Cognitive performance was assessed through various cognitive tests. We used the Behavioural Assessment and Research System (BARS) as cognitive test, employed ten tasks to assess participants' cognitive performance. Response Speed and Error Rate were the main outputs.

The exposure procedure began with a 20-minute introductory session, followed by a 35-40 minute cognitive test session. Both before and after the cognitive test, a paper-based questionnaire was used to collect perceptions such as thermal sensation and air quality. The questionnaire also collected potential confounders of the cognitive results, such as gender, age. Raised symptoms were collected after the exposure. Univariable multilevel linear regression models were used for data analysis. Participants' perceptions were analysed by ANOVA, followed by pairwise comparisons to explore interaction effects.

The impact of acute indoor TVOC exposures

This study used a 1x3 within-subject single blind design. Three conditions are shown in **Table 1**. The study comprised 33 participants, most of whom were postgraduate students (66.7%), Chinese speakers (84.8%), and 91% were in the age group 20-28 years.

Result shows in eight out of ten tasks, reaction speed was generally higher at elevated TVOC levels. But only the one task demonstrated a significant difference between low levels, 333 (45ms), and medium-high levels, 385 (72ms), p=0.003. Reaction speed increased by 23 ms (7%) when exposed to the medium-low level, and by 52 ms (16%) when exposed to the medium-high level. Therefore, from the univariable model, it cannot be concluded that acute exposure to medium-low or medium-high TVOC levels has a significant effect on reaction speed. **Figure 1** displays the mean error rates for each cognitive task. Eight out of ten tasks showed a numerical increase from low to higher TVOC levels. Univariable regression models indicated significant effects in the following five tasks: MTS, RLT, SAT, SRT, and DST. Across these tasks, the average error rate was 2.7% higher at the medium-low level compared to the low level, and 4.9% higher at the medium-high level than at the low level. Therefore, acute TVOC exposure affects accuracy performance, but the effect is only evident at medium-high TVOC levels.

Table 1. *Conditions of Experimental study 1.*

	VOCs Levels		
	Low	Medium-low	Medium-high
TVOC Concentration	0-300 μg/m³	1000±200 μg/m³	2000±200 μg/m³

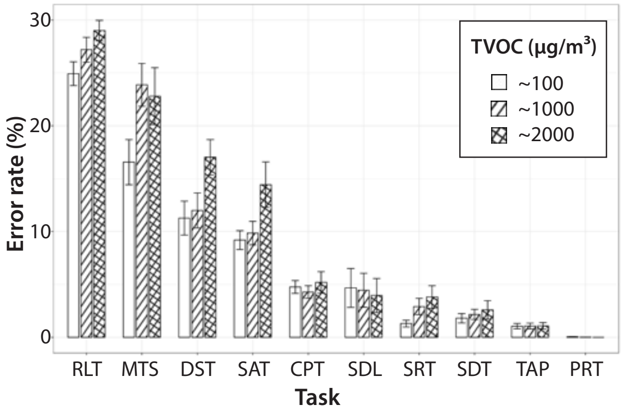

Figure 1. Error rate of each cognitive task under three levels of exposures (mean (SE), n=99).

ANOVA analysis shows for perceived air quality, there was a significant main effect of TVOC level and a significant interaction effect between TVOC level and time. Participants perceived worse air quality at higher TVOC levels. Post-hoc comparisons highlighted that participants were more likely to report "worse air quality" at elevated TVOC levels with increased exposure duration (**Figure 2**).

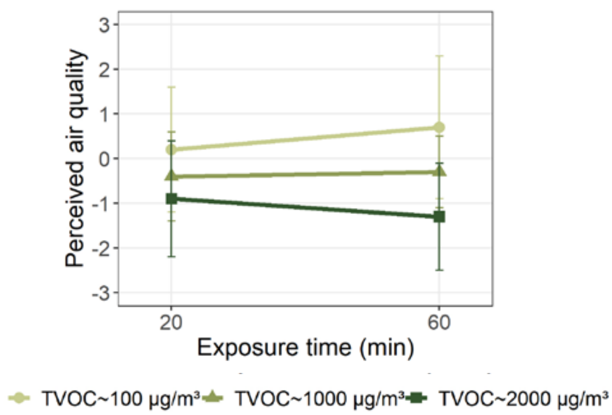

Figure 2. Subjective assessment of perceived air quality (mean (SD), n=99).

After the exposure, there was a marked increase in symptoms reported across all conditions. Participants exposed to higher levels of TVOC were more likely to report symptoms by the end of the experiment. The most commonly reported symptoms included dizziness, fatigue, and eye irritation. Univariable logistic regression analysis showed that eye irritation was significantly associated with medium low TVOC exposure.

The combined impacts of indoor temperature and TVOC

This study utilized a 2x2 within-between participant single-blind design. The temperature served as the within-participant factor, while the TVOC level acted as the between-participant factor (see **Table 2**). The study comprised 71 university students, with 35 participants in the low TVOC group and 36 in the medium-low TVOC group. The majority of participants were postgraduate students (74.6%) and identified as Chinese speakers (83.1%), with 83% of them aged between 20 and 28 years.

For reaction speed, only one task, showed a significant effect, indicating a 46ms (12%) increase in reaction speed at 28°C compared to 23°C. Regarding the impact of TVOC, only two tasks showed significant effects, with an average decrease in reaction speed of 110ms (9%) under medium-low TVOC levels compared to low levels. No significant effects were found between TVOC levels and other tasks. Overall, the reaction speed for most tasks was not significantly associated with either temperature or TVOC levels. **Figure 3** shows the average error rates across all cognitive tasks. A numerical increase in errors was observed at 28°C for most tasks, irrespective of TVOC levels. Five of the ten tasks were significantly impacted by temperature. On average, the task error rates were 3.5% higher at 28°C compared to 23°C. Overall, high temperature significantly impacts accuracy performance, while the impact of TVOC levels was unclear.

The study found a trend that medium-low TVOC levels might enhance the effect of temperature. When using 23°C as the reference category and grouping by

Table 2. *Experiment setting.*

Low TVOC group		Medium-low TVOC group	
TVOC: 0 - 300 µg/m³ Sample size: 35		TVOC: 1000 ± 200 µg/m³ Sample size: 36	
Low temp. 23°C	High temp. 28°C	Low temp. 23°C	High temp. 28°C

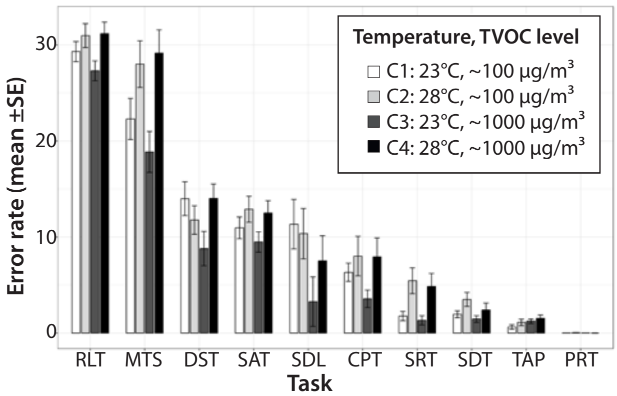

Figure 3. Mean error rate (%) of each cognitive task *in study 2.*

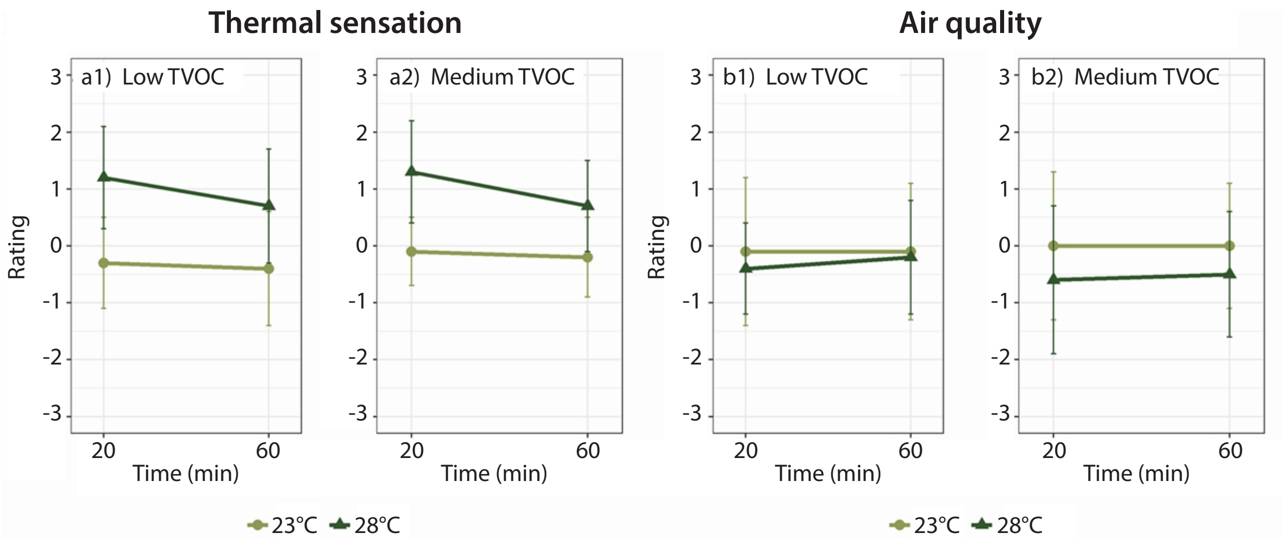

Figure 4. Participant perception average rating at 20 and 60min exposure, mean (SD). Thermal sensation (a, -3 "Extremely cold" to 3 "Extremely hot"); air quality (b, -3 "Extremely bad" to 3 "Extremely good").

TVOC level, an increase in temperature from 23°C to 28°C resulted in an average error increase of 2.4% at the low TVOC level and 5.2% at the medium level. However, the interaction is statistically insignificant. The temperature impact was significant for most tasks at the medium-low TVOC level but not at the low level. Therefore, the interaction effect of temperature and TVOC exposure remains to be validated.

There was a significant interaction effect between temperature and exposure time. Exposed at 28°C resulted in a thermal rating decrease of about 0.5, shifting from "feeling hot" toward "neutral" throughout the exposure period (see **Figure 4a**). Pairwise comparison indicated that such change was significant regardless of TVOC levels, demonstrating a clear instance of thermal adaptation over time at elevated temperatures. The perception of air quality was significantly impacted by temperature variations; participants rated the air quality as "Slightly bad" when exposed at 28°C (see **Figure 4b**). After 60 minutes of exposure, the average increase in participants reporting at least one symptom was 33%. Frequently reported symptoms included eye irritation, fatigue, dizziness, headache, and stuffy nose, with eye irritation being the most frequently reported symptom across all conditions.

Conclusion

2000 μg/m³ TVOC level had a significant effect on accuracy performance. A temperature of 28°C significantly increased error rates on various cognitive tasks among university students, while no conclusive impact on reaction speed was observed. Additionally, no significant interaction effect between temperature and TVOC was observed. Significant impacts were noted in attention, short-term memory, and working memory tasks. Subjective perceptions of air quality worsened at higher TVOC levels, with the highest TVOC exposure triggering the most symptom reports. Commonly reported symptoms after the experiment included eye irritation, fatigue, dizziness, headache and stuffy nose.

The current TVOC standard is generally applicable since cognitive performance is minimally affected at 1000 μg/m³. However, future indoor overheating may occur more frequently, potentially exacerbating the cognitive effects of indoor temperatures, especially in newly built and renovated structures. The higher TVOC exposure may negatively affect memory, wellbeing, and satisfaction with indoor spaces. Therefore, after new construction or renovation, monitoring TVOC levels is crucial. If elevated levels are detected, installing air purifiers with activated carbon filters or enhancing mechanical ventilation can help mitigate these effects. In addition, future standards may need to classify TVOC limits according to different temperature ranges. Specifically, stricter TVOC limits could be established for higher temperatures. This adjustment becomes particularly important during the summer, as buildings with insufficient ventilation are more likely to experience overheating and elevated TVOC levels simultaneously.

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ARTICLES

The impact of climate change on children's cognitive performance in English school building stock

Keywords: Schools, Retrofit, Climate Change, Cognitive Performance

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Research background

In the UK, there are around 9 million children in schools, spending most of their learning time in classrooms. By learning knowledge and skills across different subjects, children develop their cognitive function that fosters critical thinking, problem-solving abilities, and a broader understanding of the world schools [1]. In classrooms, this process is affected by many factors, such as curriculum design, quality of instruction, and classroom environment (including social and physical environment) [2]. Among these, the physical environment plays a crucial role in children's cognitive performance in classrooms. For example, high indoor temperature increases the burden of human's thermoregulatory system and suppress brain neural activity [3], often leading to headache, fatigue and distraction, and therefore, impair the cognitive performance of children. Thus, maintaining good classroom environment is essential to avoid cognitive function impairment [4].

Climate change is leading to hotter and drier summers in the UK, yet many school buildings were constructed without consideration for the potential impact [5]. In addition, schools often have high occupancy densities and intensive use of teaching devices, resulting in significant internal heat gains. On-site surveys have indicated that many classrooms lack adequate natural ventilation and are not equipped with mechanical cooling systems [6-8], making them vulnerable to overheating. However, empirical evidence remains limited regarding the extent to climate change may impair cognitive performance of school-aged children in England.

Previous experimental studies have attempted to explore the exposure - response relationship between indoor environmental parameters to cognitive performance. However, these studies derived the relationship based on a small sample of participants, limiting the generalizability of their findings to broader populations. Some studies [9, 10] have developed the exposure-response function linking cognitive performance to indoor temperature/air quality by meta-analysis. By combining data from multiple studies, these analyses increase statistical power and enable the application of the resulting functions to larger populations.

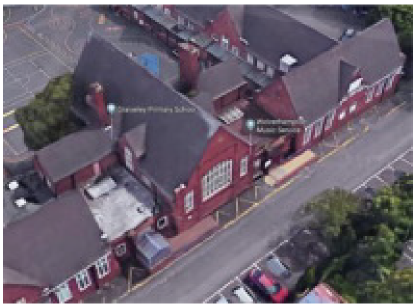
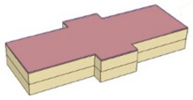
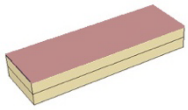
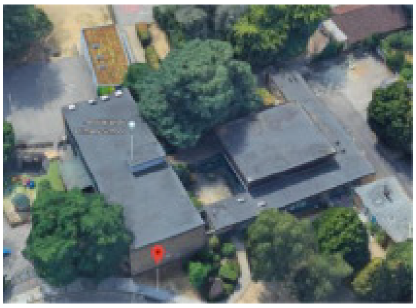
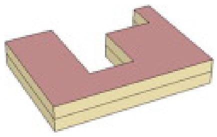
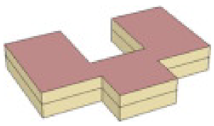
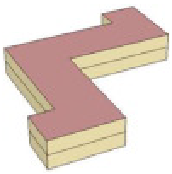
This study investigates the impact of climate change on children's cognitive performance in English secondary schools, using representative schools from three regions: Thames Valley (Southern England), West Pennines (Central England), and the Borders (Northern England). Future indoor temperatures were predicted using EnergyPlus with Chartered Institution of Building Services Engineers (CIBSE) weather files. Cognitive performance was then estimated using established temperature-performance functional relationships. The study also evaluates two mitigation strategies: improved ventilation and air-conditioning by comparing their effectiveness in reducing cognitive performance loss caused by climate change.

Methodology design

School building models

There are around 3400 secondary schools located 13 climate regions in England [11]. Due to the high computational demand of modelling each school individually, this study adopted an archetype-based modelling approach, developing a small number of representative models to reflect the broader school building stock [12]. The archetype approach first categorised English school buildings by construction era, as each period is associated with characteristic geometry and insulation levels. 'Seed models' were then developed based on these typical features (**Table 1**).

Table 1. The built form and built-up characteristics of each 'Seed' model (GF: Ground Floor. EW: External Wall. R: Roof).

Construction era	Representative schools (from Google Map)	'Seed models' (with typical geometry)	Typical U-value (W/m²-K)
Pre-1919			GF: 1.5 EW:1.9 R: 3.0
Inter-war			GF: 1.5 EW:1.9 R: 3.0
1945-1966			GF: 1.4 EW:1.8 R: 2.0
1967-1976			GF: 1.4 EW:1.0 R: 1.3
Post 1976			GF: 0.82 EW:0.85 R: 0.63

These models were further refined to account for regional variations in average building height and floor area using Property Data Survey Program (PDSP) datasets. For schools in each of the three selected regions - Thames Valley (N = 230), West Pennines (N = 75), and Borders (N = 32) - 15 archetype models were generated by scaling the 'Seed models' accordingly (**Figure 1**).

Each archetype includes a main building (representing the majority of school space) and an additional building (representing remaining facilities). Operational parameters were derived from National Calculation Method (NCM) and BB101 school design guidelines. Simulations were run from May to September, excluding weekends and holidays.

Cognitive performance prediction

Cognitive performance was estimated using the by the function developed by Worgocki et al., 2019 [9].

$$RP = 0.2269\, t^2 - 13.441\, t + 277.84 \quad (1)$$

Where t represents the indoor temperature, and RP represents relative performance at a specific temperature. This function is valid for children aged 9-18 and for indoor temperatures between 20°C and 28°C. performance at and below 20°C was normalised to 100%, based on Wargocki and Wyon [13]. for temperatures above 28°C, it was capped at the level observed at 28°C (79.4%) due to limited empirical evidence.

To quantify the impact of elevated temperatures, Cognitive Performance Loss (CPL) was used as a Key Performance Indicator (KPI), defined as:

$$CPL_t = 100\% - RP \quad (2)$$

CPL was calculated based on predicted indoor temperature on an hourly basis using EnergyPlus, with hourly CPL values ranging from 0% to 20.6% across all temperature levels. These hourly CPL values were then aggregated at the school or regional level to reflect the overall performance.

Weather files

The weather files chosen for this study were derived from CIBSE weather data sets, which are the standardized weather data in the building industry in the UK. Future climate scenarios were represented using data for three periods: 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099). Design Summer Year (DSY) files for London, Manchester, and Newcastle were selected to represent the climate conditions of the Thames Valley, West Pennines, and Borders regions, respectively, and were used as climate inputs for the school building models.

Results

The impact of climate change on cognitive performance

Figure 2 illustrates the distribution of hourly CPL for children across 15 school archetypes, with each sub-graph corresponding to one archetype. Within each sub-graph, three boxplots represent the hourly CPLs under three future climate periods for a given school type. For each school in a given climate period, hourly CPLs were area-weighted averages across all classrooms, with a total of CPL values for the simulated period.

A clear upward trend in CPL is observed across all archetypes, with boxplots becoming progressively flatter and median CPLs (orange lines) increasing

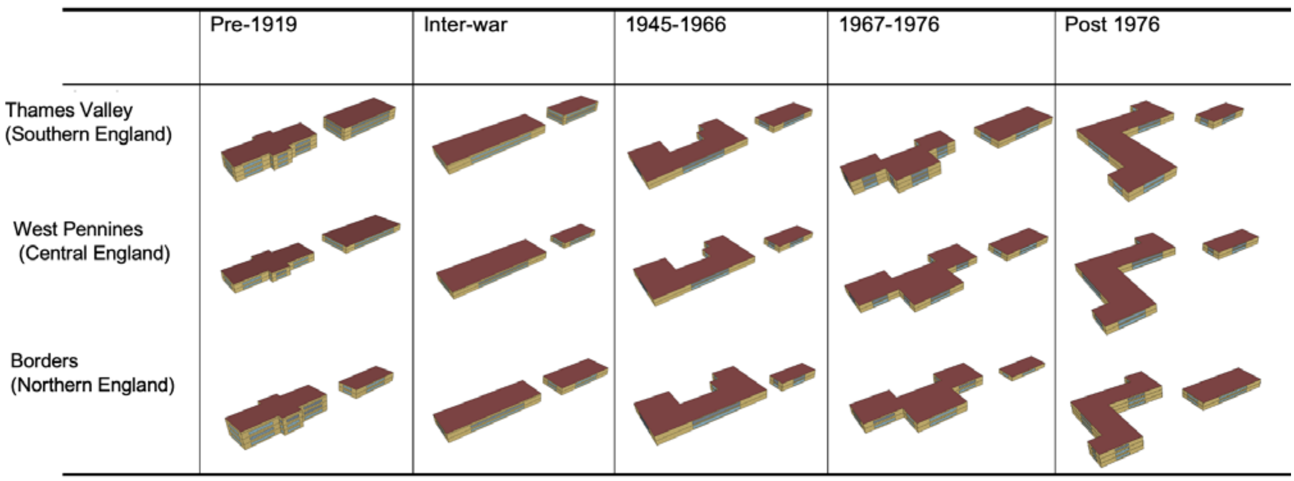


Figure 1. The school archetype models for the three representative regions.

from the 2020s to the 2080s, showing a consistent shift toward higher cognitive performance loss as outdoor temperatures rise. This pattern is particularly pronounced in Southern England schools, where by the 2080s, CPLs reach 20.6% in most hours during warmer months under London climates.

In comparison, schools in Central and Northern England display relatively better conditions in the 2020s. For instance, in Central England schools, the median CPL in the 2020s is 16.0%, and in Northern England, it is even lower, at approximately 13.0%. However, the rising temperatures over the decades drive significant increases in CPL across these regions as well. By the 2080s, the median CPL for Central England schools reach approximately 19.0%, while Northern England schools approach a median of 18.0%. Despite these increases, Northern schools remain slightly less impacted than their Southern and Central counterparts, benefiting from cooler baseline temperatures. Nevertheless, the narrowing interquartile ranges across all regions indicate that the majority of children, regardless of location, will experience conditions leading to near-maximum CPL in the 2080s.

To assess whether CPL distributions differ significantly among school archetypes within the same region and climate period, Kruskal–Wallis tests were conducted. As shown in **Table 2**, none of the comparisons yielded statistically significant differences ($p > 0.05$), indicating that within-region variations among archetypes are minimal. Therefore, future local climates are likely to exert broadly uniform effects on children' cognitive performance.

Table 2. *Results of K-W test for schools in each region in 2020s, 2050s and 2080s*

Region	Climate period		
	2020s	2050s	2080s
Southern England	0.16	0.30	0.60
Central England	0.12	0.09	0.26
Northern England	0.41	0.35	0.28

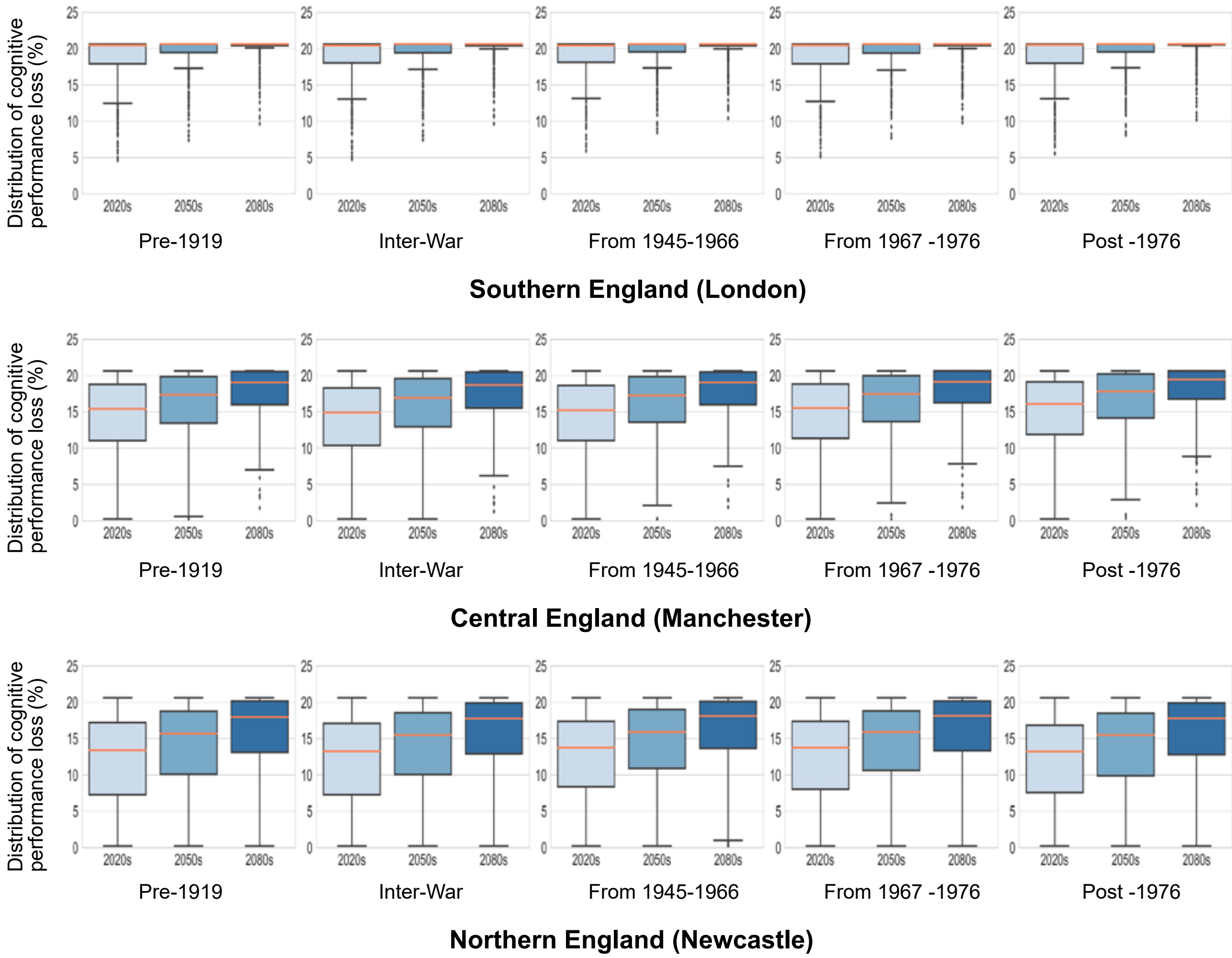


Figure 2. The distribution of hourly CPLs of pupils during warmer months in Southern, Central and Northern England schools under future climates.

The CPLs of secondary school children by climate regions were explored by aggregating the hourly CPLs of all school archetypes in each region. To be more specific, there are 5 school archetypes in each region, and the study calculated hourly CPL for a total of 2652 hours. **Figure 3** shows the frequency distributions of all school hours in the three regions in future climates. A categorisation approach was proposed to better compare and visualize the overall CPLs in the following analyses: No loss (CPL = 0%), Minimal loss (0% < CPL ≤ 5%), Moderate loss (5% < CPL < 20.6%) and Severe loss (20.6%).

The results indicate that outdoor climates have different impacts on schools at the regional level:

Southern England: Schools in this region have minimal hours categorized as 'No loss' and 'No significant loss' in future climates. There are around 59.8% of hours in which children experience severe cognitive performance loss (20.6%) under 2020s climate scenario, and the hours categorized as 'Severe loss' rise to 81.1% in 2080s climates, both of which are much higher than those in the other two regions.

Central England: for schools in this region, the majority of hours (78.6%) fall under the category of 'Moderate loss' in all future climate periods. However, due to an increase in hours with severe CPLs (38.1%), the frequency of hours at 'moderate loss,' 'no significant loss,' and 'no loss' will decrease under climate change.

Northern England: for schools in this region, 11.3% of hours experience 'no loss,' while only 7.5% of hours are classified as 'severe loss' in current climate. As the climate warms, the percentage of hours with 'severe loss' is projected to rise to 26.1%, while the percentages of hours categorized as 'no loss' (1.6%) and 'no significant loss' (7.7%) decrease in the 2080s.

Ventilative cooling to mitigate climate change impact

The impact of increased ventilation rates in classrooms on cognitive performance were examined. Two ventilation rates were tested: 8 ℓ/s-p and 15 ℓ/s-p, in comparison with the baseline ventilation rate (5 ℓ/s-p).

Within each climate period, increasing the ventilation rates has demonstrated positive impacts on schools (**Figure 4** and **Figure 5**), resulting in a higher proportion of hours with CPLs categorized as 'no loss' and 'no significant loss' at 15 ℓ/s-p compared to 8 ℓ/s-p. However, average CPLs at higher ventilation rates rise, and the difference in median CPLs between the baseline and a higher ventilation rate diminishes across all regions over the future climatic periods. For instance, in Southern England schools, the median CPLs increase from 14.1% in 2020s to 18.0% in 2080s when the ventilation rate is set at 15 ℓ/s-p. In Central England schools, the median CPLs rise from 1.9% to 10.0%, while in Northern England schools, they increase from 0.0% to 7.1%. This implies that in 2020s, higher ventilation rates prove more effective in improving cognitive performance, but their impact weakens in the 2050s and 2080s due to the rising outdoor temperatures.

In summary, ventilative cooling has positive effects on the cognitive performance of children in all three regions, while its effectiveness will be limited in 2050s and 2080s because of the warmer climates.

The potential of set-point temperature control on the cognitive performance of children by introducing air conditioning were examined (**Table 3**).

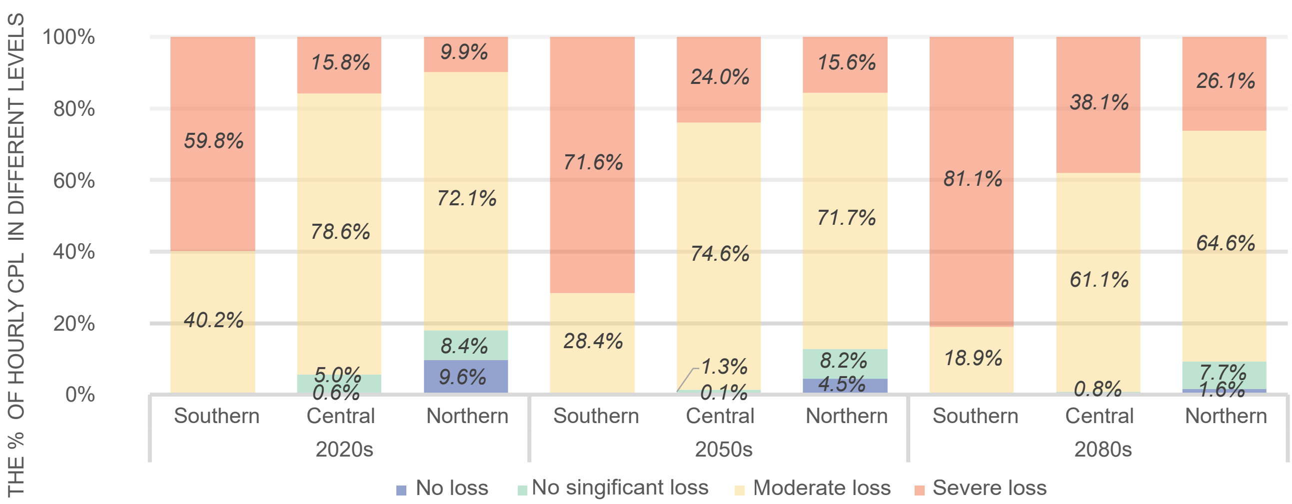


Figure 3. The frequency distributions of hourly CPLs within different levels in English schools per region.

Table 3. *The CPL of children in English schools in changing climate scenarios, per climate region, due to different ventilation rates.*

		2020s			2050s			2080s		
		Baseline (5 ℓ/s-p)	8 ℓ/s-p	15 ℓ/s-p	Baseline (5 ℓ/s-p)	8 ℓ/s-p	15 ℓ/s-p	Baseline (5 ℓ/s-p)	8 ℓ/s-p	15 ℓ/s-p
Southern England	Median CPL (%)	20.5	18.1	14.1	20.6	19.1	16.4	20.6	19.4	18.0
Central England	Median CPL (%)	15.4	9.7	1.9	17.3	12.6	5.8	19.1	15.4	10.0
Northern England	Median CPL (%)	13.5	7.1	0.0	15.7	10.2	2.3	18.0	13.4	7.1

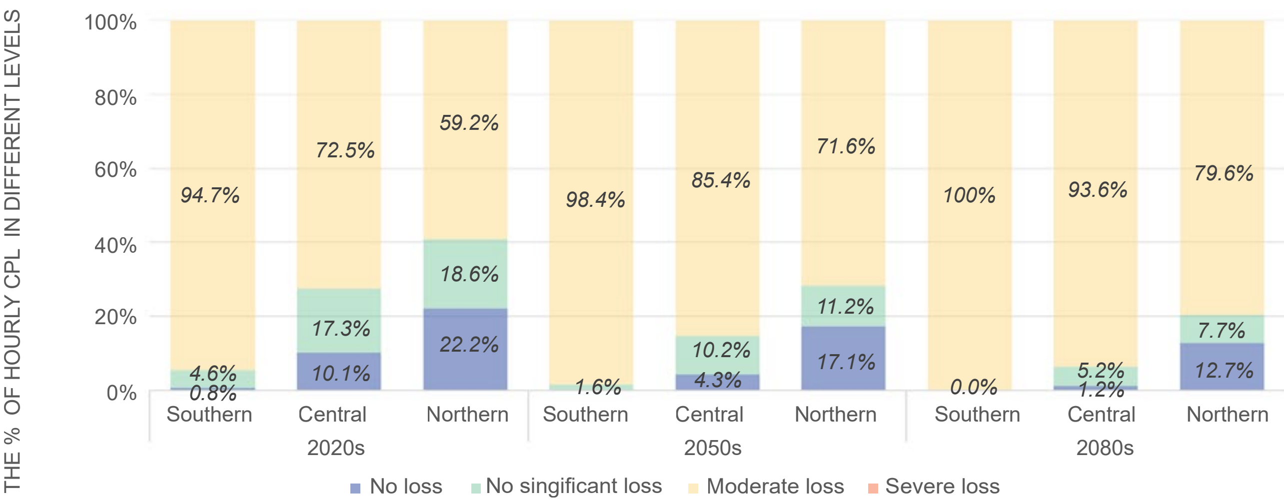


Figure 4. The frequency distributions of hourly CPLs within different levels in English schools per region at ventilation rate of 8 ℓ/s-p.

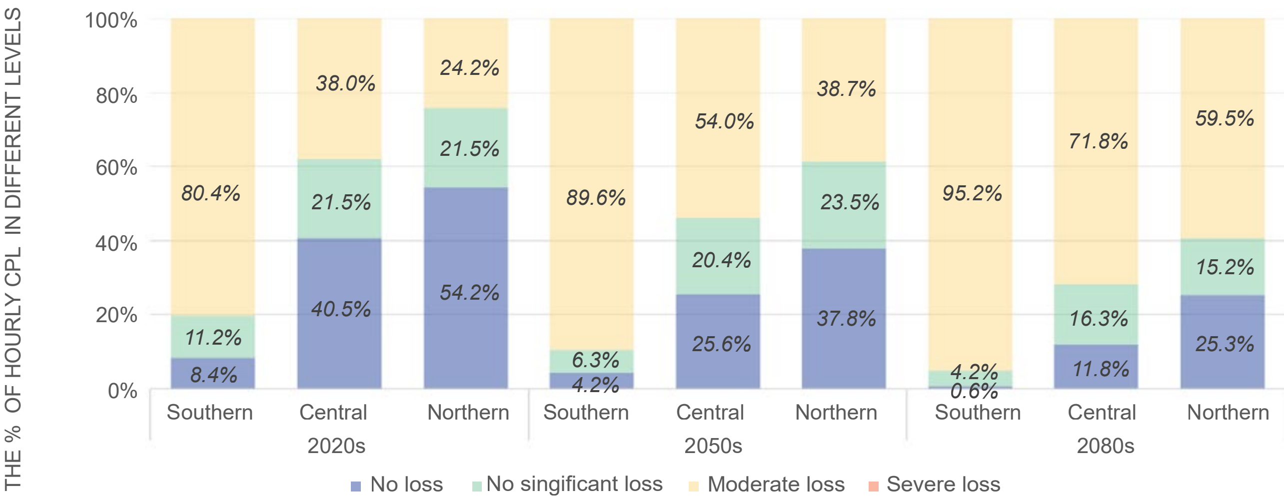


Figure 5. The frequency distributions of hourly CPLs within different levels in English schools per region at ventilation rate of 15 ℓ/s-p.

To ensure that the classrooms remain within satisfactory levels, CIBSE Guide A recommends the summer operative temperatures in teaching space should be kept from 21°C to 25°C. Therefore, 21°C and 25°C, as the border recommended values, were chosen for the analyses in this section. The air conditioning is assumed to operate when the classroom temperature is above the set-point during the occupied hours in all schools. In these two scenarios, the ventilation rates are maintained at baseline ventilation rate (5 ℓ/s – person) to meet minimum fresh air supply requirements for the children.

It should be noted that median CPLs are different at the same set point in three regions in 2020s and 2050s, with schools in Central and Northern England having median CPLs of 1.3% and 2.9% less than schools in Southern England. This is because average outdoor temperatures projected in future DSYs in Central and Northern regions remain relatively low (less than 15°C) during May, June and September, and therefore the classroom temperature may not reach the 25°C set point temperature during these months. Since the classroom remained ventilated below 25°C, ventilation can bring cooler outdoor

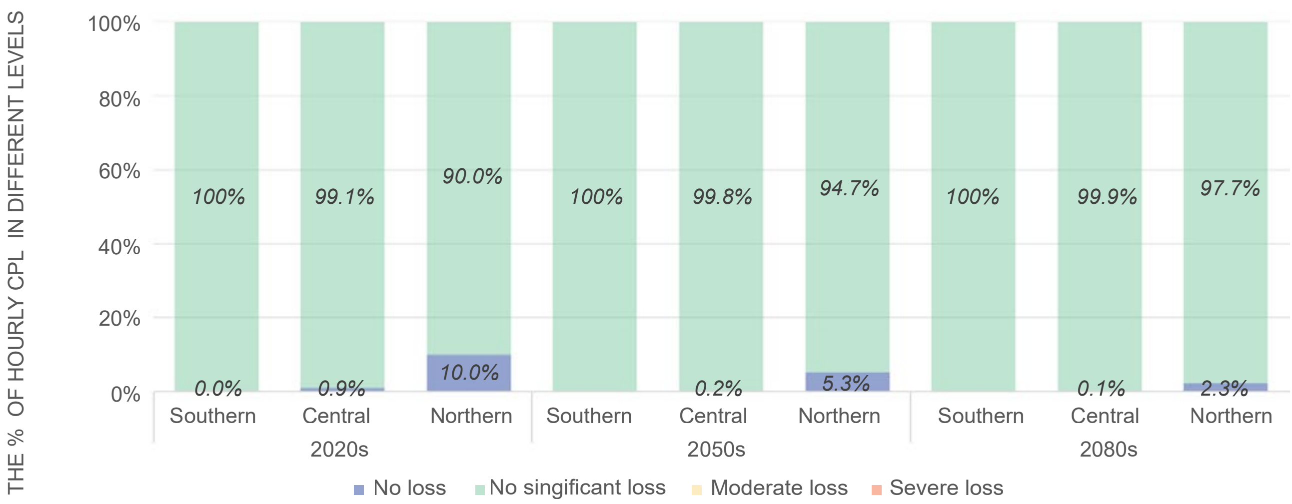


Figure 6. The frequency distributions of hourly CPLs at different levels in England per region in future climates at set-point temperature of 21°C.

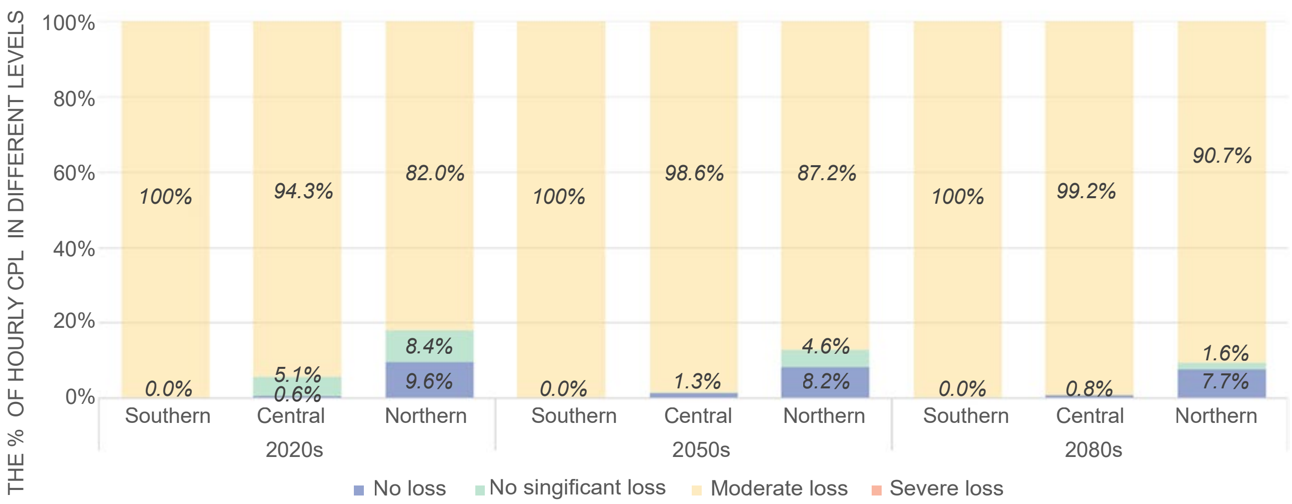


Figure 7. The frequency distributions of hourly CPLs at different levels in England per region in future climates at set-point temperature of 25°C.

Table 4. The CPL of children and cooling load of schools in England in changing climates per climate region.

		2020s			2050s			2080s		
		Baseline (no AC)	25°C	21°C	Baseline (no AC)	25°C	21°C	Baseline (no AC)	25°C	21°C
Southern England	**Median CPL (%)**	20.5	16.4	4.4	20.6	16.4	4.4	20.6	16.4	4.4
	Cooling Load (kWh/m²)		19	39		25	46		33	54
Central England	**Median CPL (%)**	15.4	15.1	4.4	17.3	16.2	4.4	19.1	16.4	4.4
	Cooling Load (kWh/m²)		5	21		8	26		13	33
Northern England	**Median CPL (%)**	13.5	13.5	4.4	15.7	15.5	4.4	18.0	16.4	4.4
	Cooling Load (kWh/m²)		3	15		5	19		9	25

air into the classrooms, resulting in a relatively cool environment during the non-air conditioning period, and therefore, decrease in overall cognitive performance loss.

As expected, setting the temperature at 21°C demonstrates a significant improvement in cognitive performance, CPLs categorized as 'Moderate Loss' and 'severe loss' are eliminated, resulting in an average CPL decrease to 4.4% across all regions during all future climate periods. **Table 4** also provides insights into the corresponding cooling loads of schools per region at the two set-point temperatures. The cooling load calculation weighted the total floor area of each school archetype within a region. Cooling loads set at 21°C will have that are 20 - 22 kWh/m² higher in Southern England schools, and 16 - 20 kWh/m² higher in Central England schools, and 12 - 16 kWh/m² in Northern England schools in the future, compared to those set at 25°C. Southern England schools exhibit greater cooling loads compared to those in Central and Northern England. By the 2080s, cooling loads are projected to reach 54 kWh/m² in Southern England schools and 25 kWh/m² in Northern England schools. By setting lower classroom temperatures, schools can significantly reduce cognitive performance loss, but at the expense of increased cooling demands, particularly in regions with warmer climates.

Discussion and conclusion

This study proposes a quantitative framework to evaluate the impact of climate change on cognitive performance in English secondary schools, using cognitive performance loss (CPL) as a KPI. Representative schools in Southern, Central, and Northern England were assessed under future climate scenarios. Results suggest that warming climates are likely to exacerbate CPL, with variations driven by local climate conditions, while differences among schools in the same region are minimal. Ventilative cooling is shown to be effective in mitigating CPL in the near future; however, its efficacy diminishes under mid- to late-century climate projections. In contrast, the adoption of air conditioning becomes increasingly advantageous in the far future, despite its higher energy demand. The proposed framework aims to provides evidence to climate risks faced by children and insights on possible optimisation pathways for English school buildings. However, as the exposure-response relationship between indoor conditions and cognition is still evolving, the findings should be interpreted as indicative projections requiring further validation. The methodology is flexible and can be refined in line with future psychological research.

References

Please see the list of references in the html-version of the article at rehva.eu –> REHVA Journal ■

Energy retrofit strategies for schools in a changing climate: a cost-optimal perspective

Keywords: Schools, Retrofit, Climate Change, Costs

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Introduction

The energy renovation of existing school buildings is becoming an increasingly relevant topic, motivated by two key needs: addressing ageing infrastructure and meeting climate policy goals. On the one hand, the need for renovation stems from intrinsic reasons: schools are often housed in outdated structures - over 50% of Italian school buildings are more than 50 years old - with poor energy performance and inadequate indoor comfort conditions. These issues are the result of both natural ageing and obsolete construction practices used before energy regulations were introduced. Addressing these shortcomings is crucial to provide adequate learning environments, which is a critical need considering that students spend a large part of their day within these buildings. On the other hand, the push for renovation is also driven by external reasons. The urgent need to meet European climate targets places strong pressure on the building sector since it is responsible for around 40% of EU energy consumption. As a result, existing buildings are required to undergo deep energy renovations aimed at reducing energy consumption and thus greenhouse gas emissions, while also improving their resilience to the impacts of climate change.

As energy renovation becomes a fundamental requirement, the key question is how to approach it effectively. Indeed, the renovation process also poses a dual challenge. While improving energy efficiency is essential to mitigate climate change, building energy performance is itself expected to change due to that same climate evolution. Consequently, failing to take climate evolution into account may result in retrofit strategies that are less effective - or even counterproductive - in the long term. This, in turn, exacerbates climate change, creating a loop where inadequate retrofits contribute to higher energy use and greater environmental impact.

To accelerate emissions reductions, and supported by increasingly available financial incentives, many renovation strategies adopt highly ambitious solutions, such as super-insulated envelopes and advanced HVAC systems that go far beyond current regulatory requirements. However, the suitability of such "over-performing" approaches must be carefully evaluated. Indeed, future climate scenarios may significantly alter heating and cooling demands, making some investments less efficient or even counterproductive. This becomes particularly relevant in public-sector projects, where high investment costs may discourage implementation. Moreover, the environmental cost of retrofit interventions - including embodied energy emissions - should not be overlooked in favour of operational savings alone.

All these factors raise important questions to consider when discussing retrofit strategies.

- Can school buildings renovated to exceed current regulatory standards offer tangible benefits when projected in future climate conditions?
- What are the most cost-effective combinations of retrofit strategies when both current and future energy performance are considered?
- To what extent does climate change impact long-term operational costs and the overall economic viability of deep renovation measures?

The following sections present the methodology adopted to explore these questions, followed by a detailed analysis of the results based on a case study representative of Italian school buildings.

Methodology

To address the above questions, the cost-effectiveness of different retrofit proposals was evaluated through a Life Cycle Cost analysis, in compliance with EN 15459:1-2018**. A school located in the Apulia Region (Southern Italy) was selected as the case study, as representative of school buildings constructed between 1945 and the mid-1970s, prior to the introduction any national energy regulations. The technical standard EN 15459:1 provides an equation to compare retrofit measures against a reference strategy, based on the total cost of the intervention (including initial investment costs, the discounted value of annual operational costs, and replacement costs). In the considered case, the reference retrofit solution was designed to meet all national regulatory requirements, including both building envelope and HVAC systems. This solution was compared to alternative retrofit options, each of which involved improving one or more parameters relative to the baseline. Six categories of interventions were considered, as shown in **Table 1**.

The LCC analysis was conducted over a 30-year time horizon. For the first 10 years, building performance and associated operational energy costs were evaluated based on current climate conditions. For the remaining 20 years, future climate conditions were considered, modelled according to the IPCC worst-case scenario (SSP5-8.5). Given the large number of potential combinations of retrofit solutions, the LCC analysis was conducted using an optimization-based approach, integrating the Pymoo optimization library (Python) with the EnergyPlus simulation engine. EnergyPlus was adopted to simulate energy consumptions, while a Genetic Algorithm manages the simulations, guiding the process toward the most cost-effective retrofit strategy (compared to law-compliant alternatives), without the need to simulate every possible combination. Indeed, these algorithms emulate the process of natural selection by evolving a starting population of random solutions to find optimal or near-optimal results according to the simulation outputs.

To assess the variation of findings due to the climate context, the results were analysed for three different climate zones, according to the Italian legislation: climate zone C (adopting Lecce as representative city, $HDD_{18°C}$ = 1122, $CDD_{18°C}$ = 907), climatic zone D (adopting Foggia as representative city, $HDD_{18°C}$ = 1566, $CDD_{18°C}$ = 784), climatic zone E (adopting Campobasso as representative city, $HDD_{18°C}$ = 2408, $CDD_{18°C}$ = 334)

Table 1. *Interventions, parameters of variation and range of variation (law-compliant values in bold).*

Code	Intervention	Parameter of variation	Range of variation		
			Zone C	Zone D	Zone E
G	U windows reduction	U windows	{**2.2**; 1.8; 1.4; 1.0}	{**1.8**; 1.4; 1.0; 0.8}	{**1.4**; 1.2; 1.0; 0.8}
SR	SHGC reduction	SHGC	{**0.35**; 0.29; 0.22}	{**0.35**; 0.29; 0.22}	{**0.35**; 0.29; 0.22}
W	U walls reduction	Insulation Thickness	{**0.08**; 0.10; 0.12; 0.14}	{**0.10**; 0.12; 0.14; 0.16}	{**0.10**; 0.12; 0.14; 0.16}
R	U roof reduction	Insulation Thickness	{**0.08**; 0.10; 0.12; 0.14}	{**0.10**; 0.12; 0.14; 0.16}	{**0.13**; 0.15; 0.17; 0.19}
S	U slab reduction	Insulation Thickness	{**0.06**; 0.08; 0.10; 0.12}	{**0.08**; 0.10; 0.12; 0.14}	{**0.10**; 0.12;0.14;0.16}
I	HVAC system efficiency improvement	Global efficiency	{[COP:**0.77**, EER: **2.05**]; [COP:3.16, EER:2.71]; [COP:3.13, EER:2.68]; [COP:1.95, EER:2.05]}	{[COP:**0.77**, EER:**2.05**]; [COP:3.16, EER:2.71]; [COP:3.13, EER:2.68]; [COP:1.95, EER:2.05]}	{[COP:**0.77**, EER:**2.05**]; [COP:3.16, EER:2.71]; [COP:3.13, EER:2.68]; [COP:1.95, EER:2.05]}

** EN 15459-1:2018 Energy performance of buildings - Economic evaluation procedure for energy systems in buildings - Part 1: Calculation procedures, Module M1-14.

Results

Optimisation results

The results of the LCC analyses for all the locations investigated are illustrated in **Figure 1**, showing the trend across 900 retrofit combinations along with the moving average.

The utility function adopted in the optimization problem compares the potential retrofit alternatives against the reference case, based on their overall costs. Specifically, it evaluates both the investment costs and the operational costs associated with each solution. This approach allows for assessing whether an alternative solution yields economic savings compared to the baseline. Such savings occur when the reduction in operational costs (mainly energy costs) outweighs the additional investment required by the alternative solution. According to the utility function, negative values indicate that a retrofit option outperforms the law-compliant reference option in terms of cost-effectiveness over the 30-year analysis period. Despite the climatic differences between locations, the overall trends appear fairly consistent. Indeed, the graphs reveal that only a limited number of retrofit combinations result in negative values of the utility function, thus performing better compared to the baseline. Specifically, the warmest climate zone (zone C) exhibits the greatest number of better combinations than the baseline option, accounting for 14 solutions of the optimization problem. By contrast, in the coldest climate zone (zone E), none out of the 900 retrofit alternatives showed an economic advantage over the baseline. Finally, climate zone D ranks in the middle, accounting for 5 solutions.

Looking at the optimal solution in each location, it is notable that - except for zone E - the best performing configuration meets law-compliant values for all retrofit measures (G, W, R, S, I) but improves solar control, using a lower SHGC value of 0.22 compared to the standard 0.35. However, the overall cost savings compared to the baseline option remain significantly limited: around €15,900 in climatic zone C and €6,900 in climatic zone D, over the 30-year period.

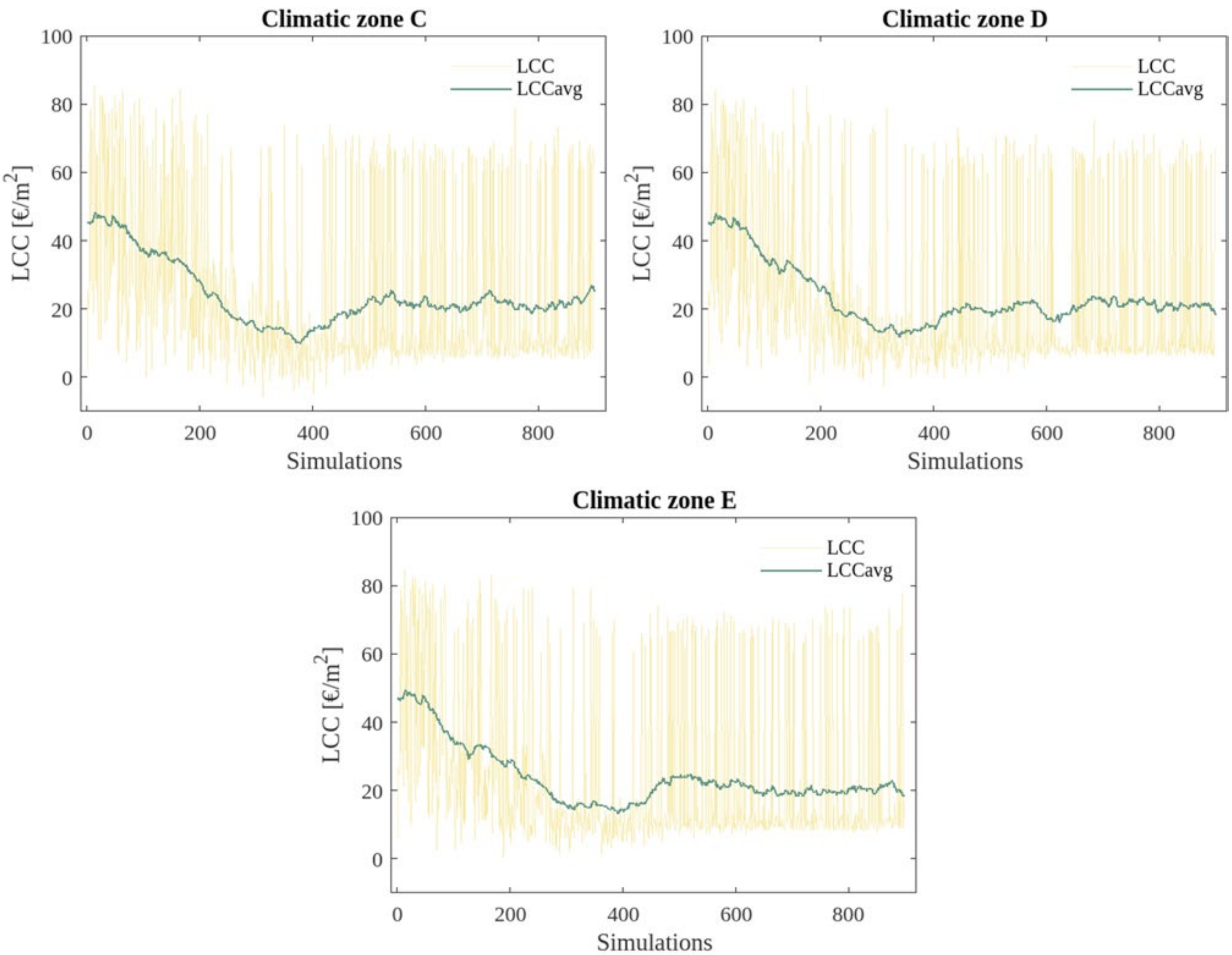

Figure 1. LCC utility function results and moving average for climatic zones C, D and E.

These limited savings can largely be attributed to the performance of the baseline retrofit, which complies with current Italian energy regulations. Indeed, the baseline already ensures good energy performance in the winter season, due to effective insulation, resulting in low heating needs. Hence, further enhancements to envelope insulation (as expected from interventions G, W, R, S) do not lead to significant additional savings, making it hard to amortize the higher investment cost required. Moreover, the effectiveness of these heating-oriented measures declines over time. In the second period of analysis - when future climate projections are applied - warmer winter conditions reduce heating demand even further. As a result, the return on investment for high-performance strategies tends to decline, particularly when evaluated over a long-term horizon.

Energy consumption

A more in-depth look at the variation in energy needs is provided by **Figure 2**, which illustrates heating and cooling energy consumption separately for the first

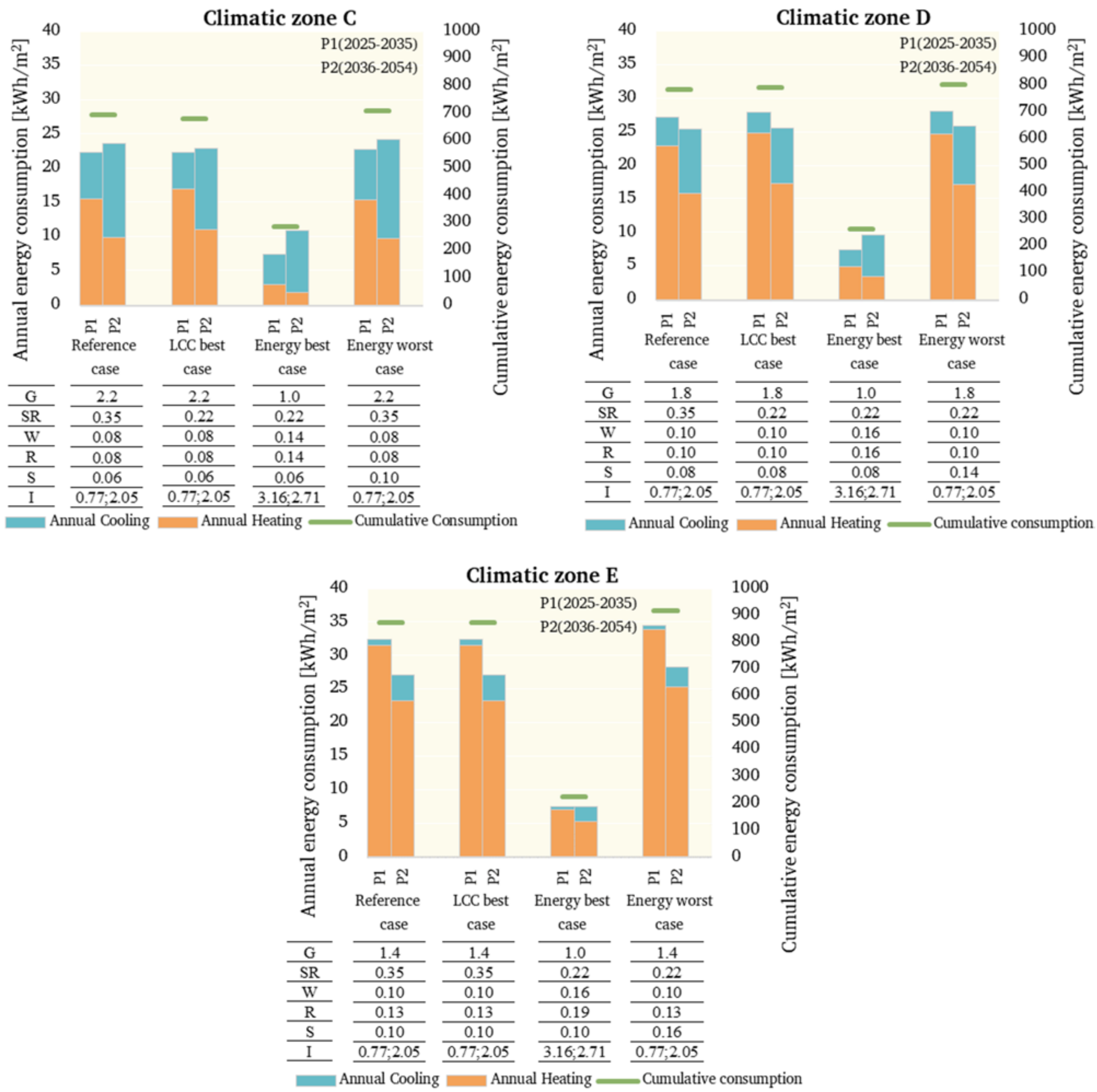

Figure 2. Bar chart showing annual heating (orange bar) and cooling (blue bar) consumption simulated in the first period of analysis (period P1, current climate) and in the second period of analysis (period P2, future climate), for climatic zones C, D and E. The total cumulative energy consumption over the 30-year analysis period is represented by green lines.

(P1) and second (P2) analysis periods, as well as the total cumulative consumption over 30 years (green line). Data is shown for the three cities investigated and four retrofit scenarios: the law-compliant baseline, the LCC-optimal solution, the energy-optimal solution (lowest cumulative consumption), and the energy-worst solution (highest cumulative consumption).

First of all, the impact of climate change on building energy needs is evident: in all the locations, heating consumption drops in the second period of analysis (P2), while cooling consumption rises, even though during the hottest months of the year (July and August) cooling is limited to office areas, given that schools are largely unoccupied. Clearly, despite the consumption variation is fairly similar, the energy balance resulting from this shift varies by climate zone. In warmer areas (Zone C), the rise in cooling demand outweighs the reduction in heating, leading to an overall increase in total energy use. Conversely, in colder zones (D and E), heating reductions are more significant and offset the increase in cooling needs, resulting in net energy savings. This growing divergence points out the need to integrate future climate scenarios into retrofit assessments, as assumptions based only on historical weather data can lead to misleading results.

A comparison between the baseline retrofit and the best performing LCC solution reveals the advantages of reducing the Solar Heat Gain Coefficient (SHGC). Indeed, although a lower SHGC slightly increases heating demand, it results in a noticeable reduction in cooling energy use and associated costs compared to the baseline retrofit option, thus generating overall cost benefits. Clearly, the benefit appears to be greater during the second period of analysis (simulated under future climate conditions), when cooling requirements grow due to the increase in temperatures. This trade-off leads to notable operating cost savings in warmer locations. In fact, all the optimal solutions identified across climatic zones C and D feature SHGC values lower than the regulatory threshold, regardless of differences in the other retrofit measures applied. This consistent trend underscores the growing importance of prioritizing cooling-related strategies. As expected, retrofit strategies that reduce SHGC exhibit the greatest economic benefits in warmer climate zones, where cooling demand is more substantial. This is clearly reflected in the results for Lecce (zone C), which show the highest cost savings. In intermediate zones like Foggia (zone D), the reduction in cooling demand is more limited and does not fully offset the slight increase in heating costs, making the overall economic benefit less significant. In colder areas, such as Campobasso (zone E), where baseline cooling needs are minimal, the measure proves ineffective from a cost-saving perspective. Nonetheless, looking at cumulative energy use over 30 years, the LCC-optimal solutions show only marginal differences compared to the baseline or even to the least effective cases, highlighting the limited room for improvement once buildings meet regulatory standards.

Although all individual retrofit measures offer high performance, the results shown in **Figure 2** make it clear that their combination plays a crucial role in determining both energy use and overall costs. For example, the LCC-optimal cases differ from the baseline scenario only by a reduced SHGC value, confirming how even a single parameter can influence cost-effectiveness. Likewise, the worst-performing energy cases differ by just one or two parameters, depending on the city, despite using otherwise high-performance components. This shows that a poorly balanced mix of measures can lead to suboptimal outcomes, increasing costs without improving performance. On the other hand, the best-performing cases in terms of energy savings achieve major reductions in heating demand, but often require excessive investments, resulting in poor cost-effectiveness. These configurations have limited impact on cooling demand, meaning the energy savings are not enough to justify the extra cost.

While only a limited number of retrofit solutions appear cost-effective compared to the baseline retrofit option, broader considerations emerge when analysing results from an energy consumption perspective. For instance, **Figure 3** compares the LCC findings with the total cumulative energy consumption variation between retrofit proposals and baseline retrofit over the 30-year period of analysis.

Notably, across all the location analysed, the results group into four distinct clusters, each one corresponding to a different HVAC system type. This recurring pattern suggests that the HVAC system selection is the dominant factor influencing both energy performance and investment costs. The largest cluster, located in the upper left side, includes all configurations using the baseline HVAC system (I0). These solutions show the lowest total costs, but the highest energy consumption compared to other clusters. It is worth noting that all the optimal solutions from the optimisation process belong to this group. In contrast, clusters based on HVAC systems I1 and I2 yield substantially lower consumption - roughly half that of I0 - but require much higher investments. Finally, solutions based on the HVAC system I3 form the smallest cluster, with energy performance close to I1/I2 and intermediate LCC values. Nevertheless, it should be considered that these results exclude potential contributions from renewable energy systems like photovoltaic panels. Incorporating PV could offset electricity use and reshape the LCC comparison, reducing the competitiveness of gas-based systems (like I0).

Overall, the size of each cluster reflects the influence of HVAC replacement on the whole retrofit effectiveness. Indeed, a smaller cluster size suggests that, once the HVAC system has been replaced, the impact of further retrofit measures becomes more limited.

From a cost perspective, represented by the horizontal extent, each cluster spans a similar LCC range, approximately 35 €/m², which correspond to around 100,000 €. Otherwise, from the energy perspective, a significant variation in energy consumption can be found within clusters. Cluster I0 shows the highest intra-cluster variability, with energy consumption

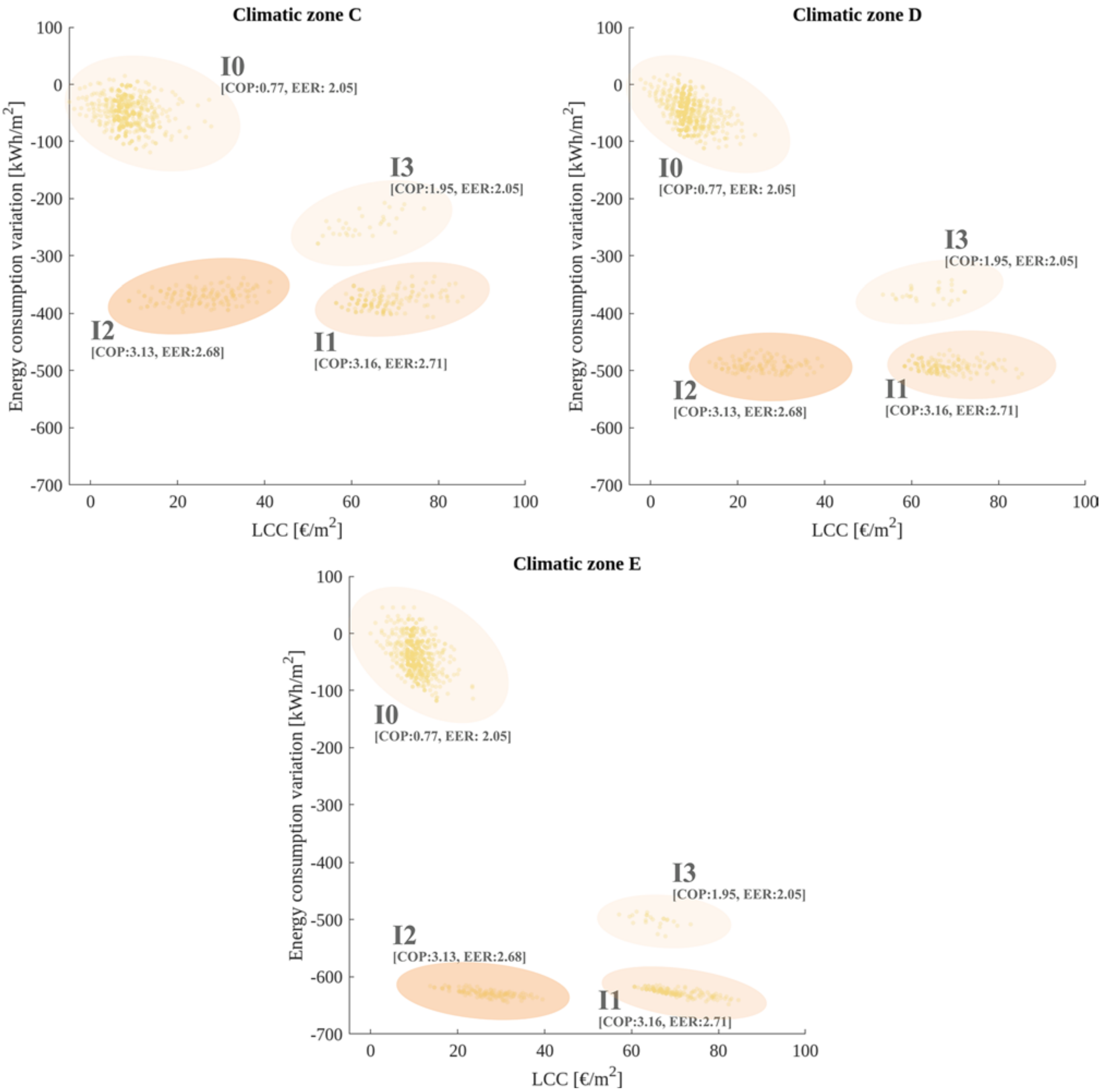

Figure 3. Total cumulative energy consumption variation between retrofit proposals and baseline retrofit over the whole period of analysis vs LCC results in all the simulations performed, for climatic zones C, D and E.

ranging up to 150 kWh/m² between solutions. The other clusters show more uniform energy performance, with intra-cluster variability decreasing from the warmest climate zone (C) to the coldest one (E), where it nearly disappears. This trend confirms that, in the considered case, the HVAC system is the dominant factor affecting energy consumption, while other retrofit measures contribute to limited energy improvements.

Despite the law-compliant retrofit already representing an optimal retrofit solution, energy consumption can still be drastically reduced by adopting other retrofit strategies. For example, in climatic zone E, switching to a high-efficiency HVAC system could reduce energy consumption by up to 75%. Similar reductions (60–70%) are observed in the other climatic zones, although such retrofit proposals fail to offer economic benefits in the medium-term, as they result in a LCC value largely above 0. By contrast, considering the cost-optimal solutions identified through the optimisation process, they are found to achieve only modest energy savings - never exceeding 8% compared to the base case - but offer a more balanced trade-off between performance and cost. However, it should be considered that the law-compliant retrofit alone ensures very low energy consumption levels, which already guarantee significantly reduced CO_2 emissions.

Conclusions

This study presents a methodology for evaluating energy retrofit strategies from a cost-benefit perspective, while accounting for future climate change impacts. The findings highlight the need of rethinking traditional design paradigms in light of ongoing climate change, particularly as building renovation will become increasingly necessary to meet the EU decarbonization targets.

Key findings

1. The widespread assumption that exceeding regulatory energy performance standards always yields greater benefits is not supported by the analysis. In the investigated case, the law-compliant retrofit already guarantees high energy performance, thus further enhancements result in limited or negative cost-benefit outcomes. Overperforming without a clear economic or environmental return may lead to wasted resources.
2. Even for buildings with low occupancy during the summer - such as schools - the study highlights that rising temperatures due to climate change will make cooling demands increasingly relevant. Among the six retrofit categories analysed, only those targeting a reduction in cooling loads, specifically through improved solar control, provided measurable economic benefits over the law-compliant baseline.
3. From the energy perspective, HVAC replacements can drastically reduce energy consumption (up to 75%), although their high initial costs are rarely offset by economic savings over the life cycle.

Emerging challenges

The study reinforces the importance of integrating future climate projections into retrofit decision-making. Neglecting these changes can lead to a misestimation of future energy needs, resulting in investments in retrofit solutions that may not remain effective or resilient in the long term.

While high-performance solutions often focus on reducing operational energy, they may substantially increase embodied energy through the use of additional materials, complex systems, and associated processes (production, transport, installation, disposal). Accordingly, future retrofit strategies must adopt a life-cycle perspective, optimizing the trade-off between operational efficiency and environmental impact, while also considering the unavoidable evolution of the climatic context.

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Ceiling Fans vs. Air Conditioning: A Pilot Study in Classrooms

Keywords: classrooms, thermal comfort, passive cooling, ceiling fans, mobile air conditioning

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Summary

In a Dutch primary school, there have been complaints about heat in the summer. Ahead of improving the HVAC system in the building, the school wants to improve summer comfort with simple measures. In a pilot study, the effectiveness and practical applicability of mobile air conditioning units and ceiling fans were compared.

Introduction

Thermal comfort in schools is crucial for overall well-being of students and teachers. High ambient temperatures can lead to discomfort and reduced cognitive performance [1]. Therefore, finding cost-effective and practical solutions to manage indoor thermal comfort during the summer months is essential.

In 2024, we were approached by a Dutch primary school facing complaints about summer heat and indoor air quality. Ahead of improving the HVAC system more radically in the future, the school wanted to enhance summer comfort at short notice with simple measures. To prevent unnecessary expenses for approximately 50 classrooms on potentially ineffective solutions, a pilot study was proposed to assess the effectiveness of two alternatives.

Prior to the pilot, various solutions were considered, taking into account e.g. costs, energy consumption, noise level, cooling effect, security, and practical feasibility. Since the school initially considered installing mobile air conditioners, this was taken as the starting point. These units are popular for their ability to provide immediate cooling and their portability. However, their high energy consumption and noise levels can be drawbacks. Ceiling fans were added to the study as a low-cost alternative. Ceiling fans are a passive cooling solution that improve thermal comfort by increasing the air speed. They are inexpensive to install, are a factor or 10 more energy efficient than mobile air conditioning units and are relatively easy to use [2]. All of these factors make ceiling fans an attractive option for schools.

The aim of the pilot was to gain insight into the effectiveness of ceiling fans and mobile air conditioning to improve summer comfort in a classroom context.

Methods

Pilot Classrooms

The pilot was conducted in four adjacent classrooms. Two additional classrooms served as reference spaces without any cooling measures. All classrooms were located on the top floor and oriented towards the South/West to assure a worst-case situation in terms of external heat load. The classrooms already had sunscreens and operable windows for passive cooling.

Two pilot classrooms were equipped with mobile air conditioning units (Comfort Line Aircobreeze R290) with a cooling capacity of 3.4 kW (**Figure 1**). These units have a noise level (when used at maximum setting) of 64 dB(A), which is significantly higher than the recommended 35 dB for installations in classrooms. The warm air from the condenser of the units was vented outside through a panel fitted in the sliding window. This setup allowed for a straightforward installation but raised concerns about burglary risk for future installation on the ground floor.

Two other classrooms were fitted with remote controlled 3-speed ceiling fans (Create Wind Sail 90W silent XL Ø163 cm), see **Figure 2**. The fans had volumetric flow capacities of 5400, 8160, and 12000 m^3/h at speed settings 1, 2, and 3, respectively; noise level in the highest setting was 48 dB(A). The CBE Fan Tool [3] was used to determine the fan configuration. One Wind Sail fan per classroom was likely to be sufficient. The fans were expected to reduce the perceived temperature by 2 to 4 degrees Celsius, assuming elevated airspeeds of up to 1,5 m/s in the occupied zone [3,4].

Monitoring Indoor Climate

The study monitored the objective and perceived indoor climate through continuous temperature measurements, thermal comfort measurements, and interviews with teachers.

Continuous temperature measurements provided data on the effectiveness of the cooling solutions over time. The temperature measurements were performed using Aranet Pro sensors. The measurement results were compared with the Class C requirements for the indoor climate in Dutch schools [5]. For classrooms with active cooling, a maximum temperature of 27°C applies. For classrooms without active cooling adaptive temperature requirements apply (maximum indoor operative temperature = 0.33 times running mean outdoor temperature + 20,4°C).

Thermal comfort measurements offered insights into the predicted comfort levels experienced by occupants.

Figure 1. Mobile air conditioning unit with exhaust via a panel between the sliding windows.

Figure 2. WindSail Ceiling fan.

Measurements of air temperature, radiant temperature, relative humidity, and air velocity were conducted at the workstation of the teacher in 3 classrooms using a Testo 400 IAQ and comfort kit. During the measurements, the sunshades were closed to limit the effect of solar radiation (increased radiant temperature). The measurements outcomes were used to calculate the PMV (Predicted Mean Vote) according to the methodology in ASHRAE 55 [6] using a clo value of 0,5 and a metabolism of 1,2 met. Results were compared with the Category C requirements from ISO 7730 (–0,7 < PMV < +0,7) [4].

Table 1. *Summary of temperature measurements (REF: reference, CF: Ceiling fan, MAC: Mobile air conditioning).*

Room	Range of daily maximum air temperature during school hours [°C]	Exceedance threshold during school hours [%]
REF1	24,4 – 29,4	70%
REF2	26,7 – 28,5	66%
CF1	25,2 – 28,1	34%
CF2	26,0 – 29,4	50%
MAC1	24,7 – 27,0	3%
MAC2	25,6 – 27,0	8%

Interviews added a qualitative dimension to the study, capturing the personal experiences of the people that worked in the classrooms during the test period. For practical reasons these interviews were limited to the teachers.

Monitoring took place during and after a week of warm summer weather. During the week of 25 June to 2 July 2024, the maximum outdoor temperatures during the day ranged from 17,3°C to 30,0°C, and the minimum outdoor temperature (day and night) was between 10,5°C and 17,2°C.

Table 2. *Summary of thermal comfort measurements and the calculated PMV. (REF: reference, CF: Ceiling fan, MAC: Mobile air conditioning).*

Room	Situation	Operative temperature [°C]	Air velocity [m/s]	PMV (ASHRAE 55)
REF1	-	28,7	0,04	1,17
CF1	fan off	28,0	0,04	0,92
CF1	fan speed 2	28,2	0,19	0,69
MAC2	airco max	26,6	0,12	0,33

Results

Temperature Measurements

The results of the continuous temperature measurements are summarised in **Table 1**. During this summer week, the temperature in the original situation exceeded the temperature threshold for approximately 70% of school hours. In the classrooms with a ceiling fan, the percentage of temperature exceedances was significantly reduced compared to the situation in the reference rooms (34-50%). Classrooms with mobile air conditioning units almost met the comfort requirements, with only 3-8% of the time exceeding the threshold temperature of 27°C.

Thermal Comfort Measurements

The results of the PMV assessments are summarised in **Table 2**. In a classroom without any cooling, the PMV was around +1 (+0,92 to +1,17). With the ceiling fan turned on, the air temperature in the classroom remained more or less the same, but the PMV-value dropped to +0,69 due to an increase of air velocity. In the classroom with mobile air conditioning, the PMV-value was even lower (+0,33), due to the lower air temperature there.

Teacher Interviews

Teachers in classrooms with mobile air conditioning units clearly appreciated the cooling effects but were bothered by the noise, which (they said) sometimes even distracted students.

Teachers in classrooms with ceiling fans also reported a positive impact on temperature perception; they even said to prefer fans over air conditioning units due to the lower noise levels. However, they did remark that fans could not be set to the highest speed (setting 3) due to paper to be blown away. The teachers in these classrooms admitted that they initially thought to prefer mobile air conditioning, but after the pilot they preferred to keep the ceiling fans instead.

Discussion

Measurement data indicate that both cooling solutions had a positive impact on indoor thermal comfort. Ceiling fans reduced the percentage of time that temperatures exceeded the comfort threshold by approximately half, while mobile air conditioning units nearly eliminated temperature exceedances. The thermal comfort assessment shows that with the ceiling fan, an acceptable comfort level (Class C) is achieved. With the mobile air conditioning, a higher quality level (Class B), is reached in terms of thermal comfort but at the expense of extra noise hindrance.

This shows that both solutions are effective to improve summer comfort, but mobile air conditioning units provide lower air temperatures.

All presented measurements are performed at the teacher's desk. We expect somewhat different and diverse results in the thermal comfort assessment for other positions in the classroom e.g. there were students are sitting. For the ceiling fan, the highest cooling effect is reached underneath the fan, while the desk of the teacher was positioned in the zone with lower air speeds which implies a relatively small cooling effect compared to the cooling effect at certain student workstations (**Figure 3**).

Also, the mobile air conditioning will not provide a uniform thermal situation throughout the space. Close to the unit higher air speeds will result in extra cooling effects.

In the interviews, teachers mention that they did not use the fan at speed level 3 because of papers blown away. They did not have complaints about draught; in speed level 2 the measured air velocities at the teacher's workstation were not higher than 0,19 m/s, which is well below the Category C summer threshold of ISO 7730 [4]. Note that normally in summer situations

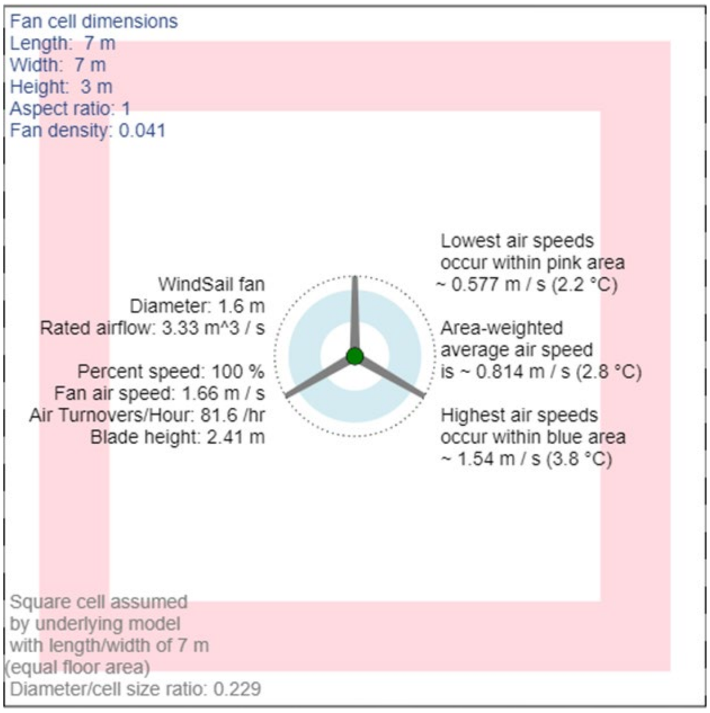

Figure 3. Cooling effect of the WindSail ceiling fan. [3]

draught complaints anyhow will be avoided if users have control over the settings of the system / the airspeed [4]. The latter is the case with both the ceiling fan and the mobile air conditioning unit.

Conclusions

The study concluded that both cooling solutions are viable options for improving thermal comfort in classrooms to, at least, an acceptable level. Ceiling fans are recommended in general for their cost-effectiveness and energy efficiency, while mobile air conditioning units are suggested for environments where higher levels of cooling are required. While mobile air conditioning units were appreciated by the teachers for their superior cooling performance, ceiling fans were preferred for their quieter operation. The noise generated by air conditioning units was a significant concern, particularly in classrooms with students who are easily distracted. The final choice between the two solutions might depend on factors such as budget, energy performance requirements, and noise tolerance.

For a cost-effective and energy-efficient solution, ceiling fans are recommended. They can be used in all classrooms and remain beneficial even with future HVAC system improvements (think e.g. of combinations of ceiling fans with centrally cooled mechanical ventilation). For environments where higher thermal comfort levels are needed temporarily, mobile air conditioning units can be considered, but quieter models should be selected than the ones used for this pilot study.

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Energy-optimised Actuation/Control of Air Heaters and Air Coolers in Air Handling Units

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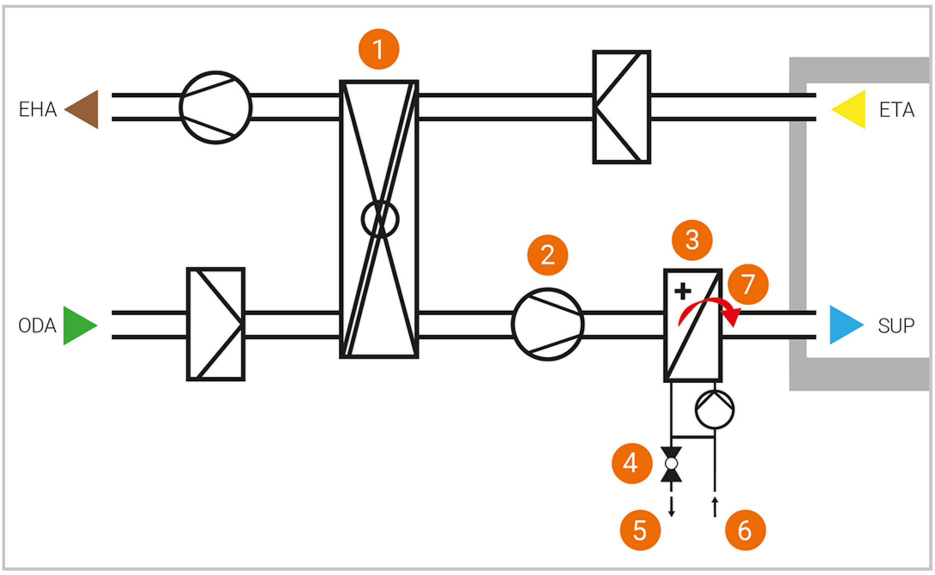
Introduction

Excellent indoor air quality is essential for our well-being and health, as we spend over 90% of our time indoors. The coronavirus pandemic has heightened awareness of the importance of healthy indoor air. In modern buildings, mechanical ventilation systems, especially air handling units, ensure high air quality by supplying outdoor air, filtering out pollutants, and regulating both air temperature and humidity.

Energy-efficient operation of these devices is essential for achieving the ambitious climate targets of the EU. Nonetheless, many air handling units are inefficient. More than 60% of existing systems in Germany are defective, and even new systems often do not achieve optimum energy efficiency [1]. The main causes often lie in the incorrect design and control of heat exchangers.

In addition to the electrical power for the fans, heat exchangers are the components in an air handling unit responsible for converting the majority of thermal energy [2]. Choosing the right valve-actuator combination to control the heat exchangers, therefore, offers significant potential savings.

The article sheds light on the causes of inefficient operation, shows practical solutions, and provides recommendations for increasing energy efficiency. It should be noted that the statements contained in this article are primarily in reference to air coolers and heaters with throttle and injection circuits. The behaviour of a depressurised mixing circuit may vary slightly, however.



	Legend
1	Heat recovery system (HRS)
2	Fan (volumetric flow, temperature, humidity)
3	Heat exchanger
4	Valve (valve position, flow rate)
5	Return (temperature)
6	Supply (temperature)
7	Thermal transfer output

Figure 1. Schematic of an air handling unit with air heater and injection circuit.

Possible causes and effects of inefficient operation of heat exchangers

The **transfer behaviour** of air-to-water heat exchangers is shown by the transferred thermal output in comparison with the water flow rate (grey dots in **Figure 2**). As the flow rate increases, the output increases logarithmically until the heat exchanger reaches saturation at higher flow rates. With constant inlet conditions, the transfer behaviour corresponds to the heat exchanger characteristic curve (blue line). In reality, however, the variability of these conditions leads to a cluster of points.

A correctly designed system generally exhibits low dispersion and ideal transmission behaviour, as shown in **Figure 2**. In practice, however, cases exist that deviate from this behaviour. These do not always have a negative effect on energy efficiency, but unfavourable scenarios can be identified by recording the transmission behaviour.

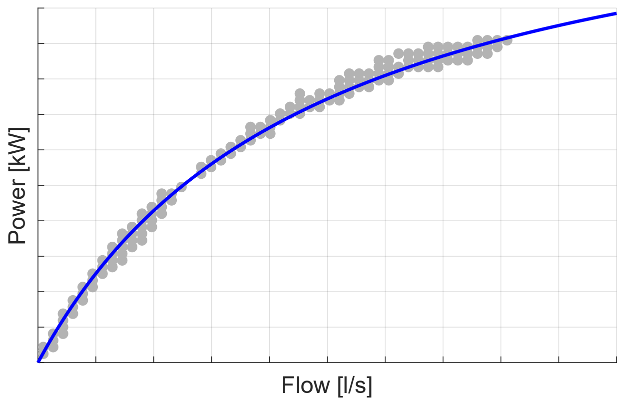


Figure 2. Heat exchanger characteristic curve with ideal transfer behaviour.

Temperature and pressure fluctuations in hydronic systems

Temperature and pressure fluctuations can appear in hydronic systems. Temperature fluctuations caused, for example, by a distribution network that has been set up to produce potable hot water, influence the output of the heat exchanger and thus the supply air temperature. The temperature control compensates for this by controlling the valve, but usually with a delay, due to the slow reactivity of the heat exchanger, temperature sensor, and controller. These kinds of changes are noticeable and undesirable in sensitive applications. Poor controller settings can even cause the system to oscillate.

Temperature changes lead to a change in the power output at a particular valve position (or flow rate). The operating points deviate accordingly from the ideal heat exchanger characteristic curve, as shown in **Figure 3**. Additional recording of the supply temperature would provide a direct indication of this situation.

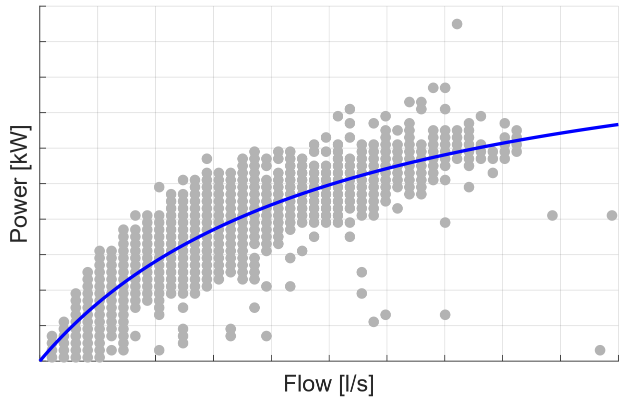


Figure 3. Dispersion of the operating points.

Pressure fluctuations occur when consumers are switched on or off. This changes the flow rate and thus the power output of the heat exchanger without directly influencing the transfer behaviour. These changes must also be compensated for by the temperature control, which can lead to undesirable effects.

Saturation operation of heat exchangers

Operating a heat exchanger in saturation reduces the efficiency of the overall system. Saturation occurs when the transferred power hardly increases with increasing water flow rate (yellow area in **Figure 4**). An increase in flow rate results in a slight increase in output, but increases the pump flow and reduces the differential temperature between the supply and the return (low differential temperature syndrome). This leads to poor efficiencies in heat generators or chillers and makes the system inefficient.

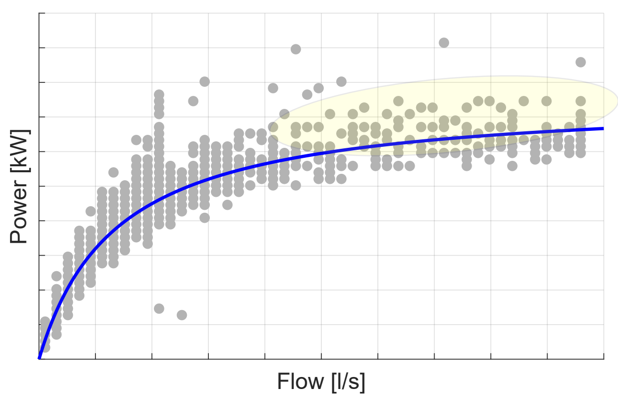


Figure 4. Transfer behaviour in saturation.

Causes for operation in saturation can be:

- Contamination of the heat exchanger on the air side due to missing/defective filters or poor maintenance
- Undersized heat exchanger
- Insufficient supply temperature

Incorrect sizing of valves

The heat exchanger in an air handling unit is designed by the manufacturer, while the valve is usually determined by the heating engineer, which can lead to non-optimal sizing of the valve. Air handling units are often designed for nominal load, but operate mainly at partial load. Dynamic heating or cooling load conditions and variable air volume flows require precise sizing of the heat exchanger and the control valve. If the valve is determined according to the pipe diameter, then this will often result in oversizing, which in turn causes an inaccurate control characteristic at partial load. Even small valve openings lead to an excessive flow rate, which causes temperature fluctuations in the supply air and a loss of comfort. These fluctuations can also influence neighbouring systems.

Valves that are too small, on the other hand, restrict the flow rate. The heat exchanger could have additional capacity in the event of extensions or changes of use, but the valve does not allow a higher required flow rate, even though it is permanently fully open (see **Figure 5**).

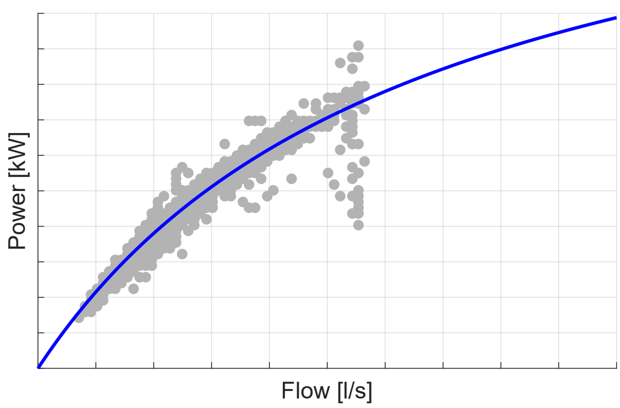


Figure 5. Limited flow rate with a valve that is too small.

Operating states do not match the design state

The design of the heat exchanger is based on heating or cooling capacity, water temperatures, water flow rate, and air flow rate. Operating states that deviate from the design can cause problems. Higher supply temperatures cause the heat exchanger to be "oversized", whereby small changes in flow rate cause large changes in output. This makes control more difficult and increases the tendency to oscillate.

The transmission behaviour in **Figure 6** shows operating points in the lower flow range when the supply temperature is too high.

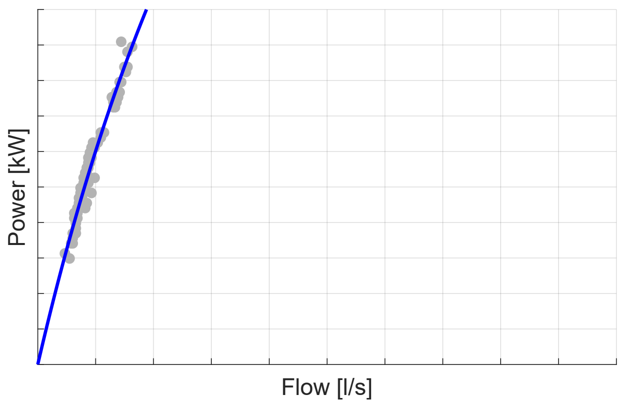


Figure 6. Transfer behaviour with a heat exchanger that is too large.

If the supply temperatures are too low, then the heat exchanger cannot transfer the required output and is operated inefficiently when in saturation. The required output is not achieved, which can also result in diminishing comfort.

Possible solutions for improving energy efficiency

The following solutions, which are in reference to the problems outlined above, can contribute to improving energy efficiency and room comfort.

Creating transparency

The availability of measured values is crucial for recognising inefficient operation of the heat exchanger or the hydronic system, especially in existing systems where the design values are often no longer correct due to modifications. Transparency also helps to identify faults in new systems at an early stage.

Important measured values such as valve position, temperatures, and water flow rate must be recorded in order to calculate the transferred output. The transmission output in connection with the flow rate represents the transmission behaviour, which in turn provides an indication of the efficiency of the system.

This data is useful only if it is processed. Digital communication (e.g. Modbus, BACnet) enables evaluation and optimisation by the air handling unit or the building management system.

Measuring and controlling the flow rate

Pressure fluctuations in a hydronic system must be compensated for by the air handling unit. This is usually done via the supply air temperature control, but this leads to slow reactivity and possible oscillations if the control is not well-tuned.

Pressure-independent valves that control the flow rate offer a more direct solution, as they compensate for pressure fluctuations at the water side and guarantee stable transmission conditions. In addition, their use enables simple hydronic balancing by setting the maximum flow rate, which saves both time and money.

Both mechanical and electronic pressure-independent valves are available. Electronic pressureindependent valves offer the advantage that the flow rate is known as a measured value and can be used for evaluation. They furthermore offer a large dynamically adjustable control range, which allows the flow rate to be adapted and incorrect sizing to be avoided.

Measuring and controlling output

The transferred output of a heat exchanger can be measured and calculated on the basis of the flow rate and the differential temperature between the supply and return. This creates transparency in the system. If this measurement is combined with a valve, then the output can also be controlled. This offers some decisive advantages in practice.

The power control enables both pressure and temperature fluctuations in the supply to be recognised and compensated for. It also ensures perfect linearization of the system and facilitates stable operation of the temperature controller, particularly in the partial load range. The performance and flow rate can be analysed over a longer period of time, which provides valuable insights for improving the system as described above.

Electronic pressure-independent valves with energy monitoring, which are referred to as energy valves, combine a flow sensor with temperature sensors and a valve. They control the flow rate and output autonomously and make all measured values available to the higher-level system via communication interfaces.

Valve as part of the air handling unit manufacturer's scope of delivery

Air handling units (AHUs) are increasingly being offered "ready-to-connect". This means that the control and field devices (actuators and sensors) are being supplied directly by the manufacturer of the AHUs as part of the scope of delivery. Often, the appropriate valve-actuator combination for controlling the heat exchangers is not supplied by the manufacturer and is then planned and installed by other trades.

Problems with the control of the heat exchanger could be avoided if the manufacturer of the AHU also supplied the valve or at least designed it. The manufacturer responsible for the sizing of the heat exchanger could thus define the appropriate valve size and avoid oversizing the valve. The integrated control of the AHU could be optimised to the valve, which improves the control quality. In addition, a communicative interface to the valve actuator could be designed so that all important data is available in the AHU. With analogue integration, important information from the valve actuator is not available to the control system or building management system.

Discussion

Possible solutions are only as good as their implementation in practice. There are often some stumbling blocks when implementing such solutions.

Creating transparency

Recording measured values initially means higher costs, but these often pay for themselves several times over during an operating period of 15 to 20 years. The recording of important values such as valve position, temperatures, and flow rate enables the performance to be evaluated transparently. Electronic pressure-independent valves with energy monitoring can automatically measure and visualise these values. The challenge often lies in integrating the valve-actuator combination into the device control system of the air handling unit. In contrast to analogue integration, with digital integration, all information is available to a higher-level system. If analogue control is unavoidable, then hybrid integration could at least be used to read out the available information.

Measuring and controlling the flow rate

Pressure-independent valves are fully developed but are not yet used everywhere as they are more expensive. The use of electronic pressure-independent valves can, however, save costs in the long term, for example by reducing the effort required for hydronic balancing and subsequent optimisation of operation.

Measuring and controlling performance

The EPBD Directive (Energy Performance of Buildings Directive) requires continuous monitoring of energy consumption. In the case of heat exchangers, it is complex to measure energy flows via the air. A simpler solution is calculation on the water side, which is reliably possible by using energy valves. The initial investment costs for energy valves are usually quickly amortised by the gains in efficiency and are economically justifiable.

Concrete recommendations for action

The following recommendations optimise the operation of heat exchangers in air handling units and contribute to achieving the EU's climate targets by reducing CO_2 emissions and saving costs at the same time:

1. Use pressure-independent valves

Pressure-independent valves should always be used, as they are considered state-of-the-art. Electronic pressure-independent valves offer additional advantages by providing necessary system transparency.

2. Use electronic pressure-independent valves with energy monitoring

These valves record the current transferred output at the heat exchanger and provide important system transparency. Their integrated functions make a significant contribution to reducing energy consumption.

3. Digital interface for control

Valves must be integrated into the control system or the building management system via a digital interface. Only in this way can the recorded data be used for evaluations that lead to further energy savings.

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Upcoming events

Please send information of your event to Ms Marie Joannes, mj@rehva.eu

2025		
21-25 June	ASHRAE Conference	Phoenix, USA
10-11 July	ISH	Iasi,Romania
6-8 August	Cold Climate HVAC & Energy	Harbin, China
24 August	Building Simulation Conference 2025 (IBPSA conference)	Brisbane, Australia
24-26 Sep	45th AIVC & ASHRAE 2025 IEQ joint Conference	Montreal, Canada
24-26 Sept	EUROVENT Summit 2025	Prague, Czechia
8 Nov	World Ventil8 Day	Brussels, Belgium
17-18 Nov	Brussels Summit 2025	Brussels, Belgium
12-14 Oct	60th anniversary of AIIR (conference)	Sinaia, Romania
29 Nov-2 Dec	ISHVAC 2025	Tokyo, Japan
10-12 Dec	56th International HVAC&R Congress and Exhibition	Belgrade, Serbia
2026		
19-23 May	Indoor Air Quality, Ventilation and Energy Conservation in Buildings conference (IAQVEC)	Los Angeles, USA
31 Jan - 4 Feb	2026 ASHRAE Winter Conference	Las Vegas USA

Interview with Dr. Zeynep Duygu Tekler by Lada Hensen Centnerová

Designing Smart Buildings with Humans in Mind:

A conversation on machine learning, personal comfort and intelligent control in the built environment

Dr. **Zeynep Duygu Tekler** is a Senior Research Associate in the Department of Engineering Science at the University of Oxford. Her research focuses on occupant-centric smart building technologies and machine learning approaches to improve energy efficiency and occupant well-being in the built environment. Prior to Oxford, she was a Postdoctoral Research Fellow at the National University of Singapore and completed her PhD at the Singapore University of Technology and Design (SUTD) under the SUTD-MIT International Design Centre in 2021.

Dr. Tekler's research has been published in leading journals, including *Building and Environment*, *Energy and Buildings*, and *Applied Energy*, with over 1,000 citations and an h-index of 15. She is a Fellow of the UK Higher Education Academy and a Junior Research Fellow at Kellogg College, University of Oxford. Her work has earned her multiple awards and recognitions, including the Seal of Excellence in Marie Curie Postdoctoral Fellowship (2025), First Runner-Up in the Oxford Net Zero Energy Hackathon (2024), and SUTD Best Research Project Award for her patented smart energy management system, Plug-Mate (2021). She was also the SUTD Champion and Asia-Pacific Finalist in the International 3MT Competition (2020), and a recipient of the Singapore International Graduate Award (2017–2021).

LHC: You are a co-author of the paper titled "Hybrid system controls of natural ventilation and HVAC in mixed-mode buildings: A comprehensive review." [1] Could you clarify what do you mean by a 'mixed-mode building'?

ZDT: A mixed-mode building combines both natural ventilation (such as operable windows, vents or other passive airflow strategies) and mechanical HVAC systems. The idea is to take advantage of natural ventilation when conditions are suitable, and switch to mechanical systems when needed. In this paper [1], we conducted a comprehensive review of control strategies in such buildings, focusing on how to effectively manage the interaction between the two systems to improve energy efficiency while maintaining occupant comfort. My previous team at the National University of Singapore, led by Prof. Adrian Chong, is pioneering research in this area.

LHC: I found a very interesting figure in that paper. Figure 1 presents a keyword analysis of the titles and abstracts of the reviewed publications, showing the averaged publication year per keyword. It looks like hybrid ventilation started with night ventilation.

ZDT: Yes, that's correct. If we look at this **Figure 1** closely, we can observe a clear evolution in research focus over time. Initially, around the early 2000s, studies on hybrid ventilation often centred around **night ventilation**, especially in connection with natural ventilation and energy saving strategies. After 2015, and increasingly after 2020, there is a shift towards adaptive control. The growing number of papers suggest that AI is gradually being introduced into our lives and implemented in building control systems. This shift reflects a rising interest in smarter and more responsive technologies for improving energy efficiency and occupant comfort.

LHC: The mentioned paper provides an overview of 5 control strategies. It starts with On-Off and PID control and ends with Fuzzy logic and data-driven control. Why do you need more complex controls than PID controllers?

ZDT: I think the complexity of control strategies depends on the building's capabilities and requirements. Nowadays, in many existing buildings, the control systems still rely on very simple, rule-based approaches — such as fixed temperature setpoints. But as buildings become smarter and more integrated with IoT technologies, there is a greater potential to optimize the performance by learning from and responding to occupant behavior. So, the simple answer is that AI enables control systems to become more intelligent — evolving from basic On-Off and PID controllers to more adaptive and sophisticated systems which respond dynamically to how occupants use the space.

LHC: I would like to go back to mixed-mode buildings with hybrid ventilation. Such buildings with good control can save significant amount of energy for conditioning spaces and at the same time guarantee good thermal conditions, but what about noise and outdoor air pollution?

ZDT: They are equally important. There are many dimensions of comfort and thermal comfort is just one aspect. Among the 74 papers we reviewed, only one addressed control strategies that also considered outdoor noise and air pollution. That said, with the advancement of smart technologies, it is getting increasingly feasible to integrate noise and air quality monitoring into HVAC control systems using real-time data. Ideally, noise levels and outdoor air pollution should be continuously monitored and factored into the building's control strategy to ensure a holistic approach to occupant comfort.

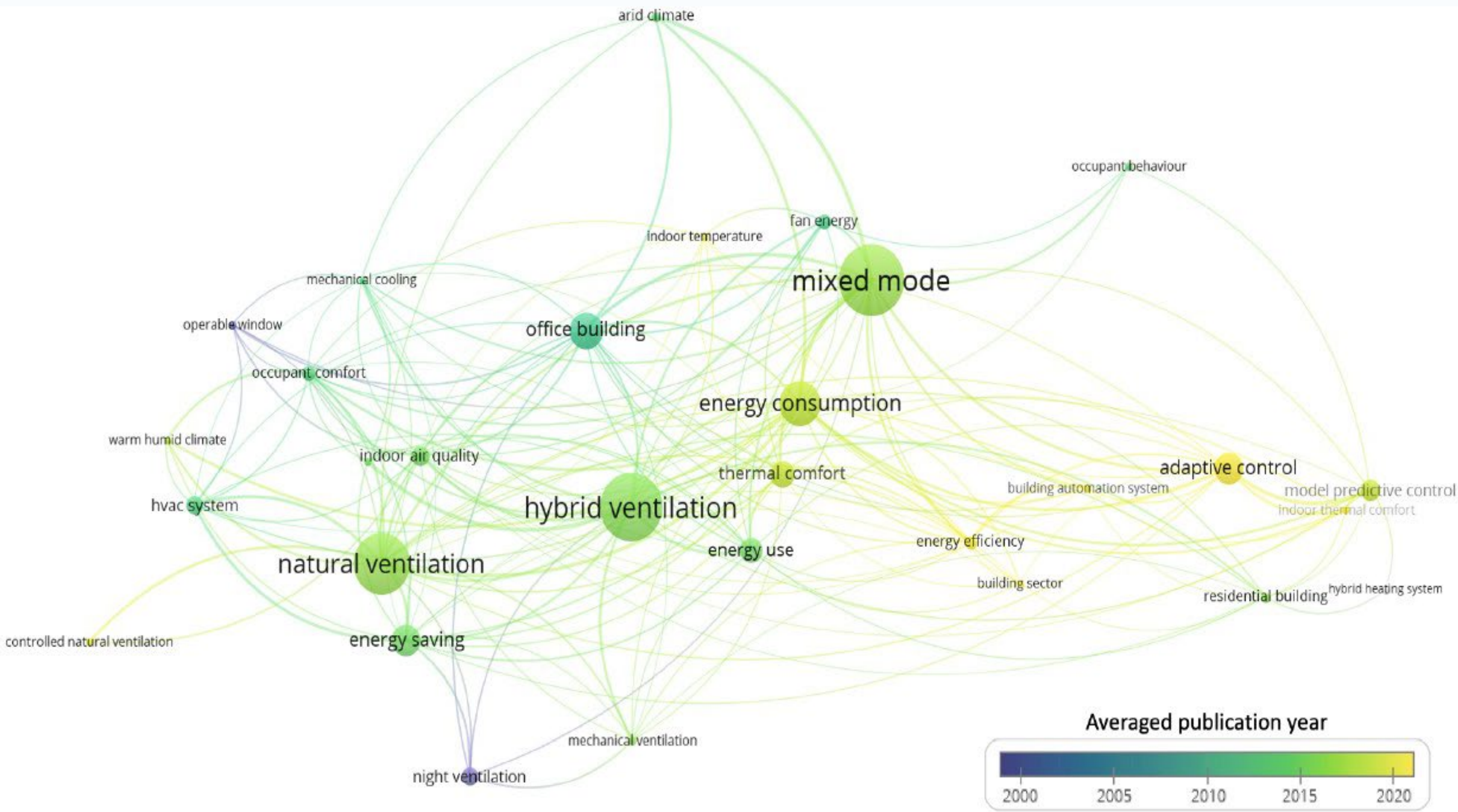

Figure 1. Keyword analysis of the reviewed publications' title and abstract.

LHC: You mentioned real-time monitoring and optimization. Let's speak about your other papers "Data-efficient comfort modeling: Active transfer learning for predicting personal thermal comfort using limited data" [2] and "Enhancing personalised thermal comfort models with Active Learning for improved HVAC controls"[3]. Can you explain what you are proposing in these papers?

ZDT: In these papers, we focused on two main goals: one is improving building energy efficiently, and the other one is improving comfort. Traditionally, thermal comfort research has concentrated on group level comfort, but there is a growing shift toward personalized comfort –models that can predict individual level comfort responses.

That is what we explored – developing models that can predict how hot, cold or comfortable occupants feel under changing room conditions on an individual level. One promising approach in this context is thermal preference-based HVAC control, which adjusts the heating and cooling setpoints based on each occupant's thermal comfort preferences to enhance both energy efficiency and occupant comfort.

The biggest challenge with personal comfort models is that they typically require a lot of user feedback, which means frequent surveys. This process can be very labor intensive, time-consuming and expensive. To address this, we leveraged **active learning**, a machine learning technique that minimizes the amount of data needed by identifying the most informative data points for training, rather than using the entire dataset. In [2], we applied **active transfer learning** to develop data-efficient thermal comfort models. In [3], we extended this work by integrating these models into HVAC control systems in a more cost-effective and scalable way.

LHC: Well, I think another problem is that people don't want to provide answers all the time.

ZDT: Yes, exactly, they don't want to be constantly bothered. And that is what makes this work particularly valuable. We're exploring how algorithmic approaches, including AI and its subbranches, can help reduce the amount of data needed to develop data-driven comfort models. The goal is to accurately predict individual level comfort without requiring extensive user input.

LHC: How far can you go to avoid collecting lots of users' feedback data?

ZDT: That really depends on the complexity of the problem and the approach used. When we developed models to predict personal thermal preferences, we found that the need for users' feedback could be reduced by up to 46% using active learning [4]. In our follow-up work [2], we combined transfer learning with active learning, and found that less than 10% of the user feedback was sufficient to achieve models as accurate as traditional ones that require 100% of the feedback. This is a significant reduction, making data-driven comfort models more scalable and practical for real-world applications.

LHC: This sounds very promising but still, first you need to collect feedback data. Can you use this approach in a new building?

ZDT: Yes, this can be done using a specific area in machine learning called transfer learning. The idea is to take models trained on data-rich buildings where we have lot of information and transfer that knowledge to a new building with limited data. In the paper I mentioned earlier [2], we explored how transfer learning can be combined with active learning through multiple experiments. Essentially, we start with a pre-trained model and fine-tune it using small amount of new data from the target building. This approach significantly reduces the amount of training data and time required, making it much more practical for real-world deployment in new buildings.

LHC: You did this study in Singapore. Could it be also used in Europe mild climate?

ZDT: Definitely. I see great potential for applying this approach in climates like the UK's, or other mild European climates. In fact, one of our planned future works is to apply the framework across buildings in various climate zones. This will help us further test and ensure the generalizability of the findings beyond the context of a tropical climate like Singapore.

LHC: Is there something else from your research, we should talk about in this interview?

ZDT: My expertise lies in applying machine learning in the built environment, with a strong focus on occupant behavior. In addition to personal thermal comfort, I am very much interested in occupancy —specifically, how people move through and use spaces over time, and its impact on energy use in the buildings. In my research at the National University of Singapore, I focused mostly on institutional buildings, while at the University of Oxford my work centred on domestic buildings.

What I find especially exciting is the challenge of integrating multiple aspects of occupant behavior, such as diverse comfort preferences and movement patterns, into responsive and adaptive building systems. "How can we design buildings and buildings systems that are not only energy-efficient, but also truly human-centric—able to anticipate and respond to the diverse needs of their users in real-time?" I believe this is one of the most important and complex challenges in creating the next generation of smart and sustainable buildings.

LHC: What is your definition of smart or intelligent building? How do you explain it to your students?

ZDT It depends on whether the students have any background in AI or machine learning. If they are completely new to the topic, I start by explaining that a smart or intelligent building is one that can learn and make decisions, and it's responsive to its environment using technology.
I often describe it a building that can sense what's happening both inside and outside of the building through various sensors – taking measurements like temperature, occupancy, light levels and air quality. It can collect and exchange data via the Internet, which is where the Internet of Things (IoT) comes into play. Based on this data, it can also make automated decisions and that's where AI becomes crucial.

For example, a smart building can automatically adjust HVAC systems, lighting or plug loads based on occupancy or time of the day – something I explored in my PhD research. So in short, a a smart building is one that uses data and intelligent systems to operate more efficiently and improve occupant comfort.

LHC: The last question. The use of AI and IoT for monitoring and optimizing buildings' energy performance consume energy, do you think that achieved energy savings are higher than energy used for AI and IoT?

ZDT: That's a great question and an important one. Yes, AI and IoT systems do consume some energy for data processing, communication, and sensor operations. However, in most cases, the energy savings they enable far outweigh the energy they consume.

That said, it's important to design these systems efficiently, choosing low power sensors, optimizing data transmission, and leveraging edge computing where possible to reduce energy overhead. So, when implemented thoughtfully, the net energy impact is positive, contributing to both operational savings and sustainability goals.

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Building the Future: **SmartLivingEPC** Final Event Showcases Digital Innovation for Sustainable Living

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Brussels, May 6, 2025 — The final event of the SmartLivingEPC project, titled *"Building the Future: Digital Innovations for Energy-Efficient and Sustainable Living"*, was successfully held in Brussels, drawing participation from policymakers, industry leaders, researchers, and project stakeholders. Organized by REHVA, this high-level conference marked the culmination of a 36-month effort under the EU Horizon framework to redefine building energy performance certification through digital transformation.

A Platform for Collaborative Innovation

The event served as a confluence of three prominent EU-funded projects: SmartLivingEPC, CHRONICLE, and SmarterEPC, all under the umbrella of the Next Generation Energy Performance Certificates (Next Gen EPC) Cluster. The agenda was designed to reflect the shared ambition to modernize EPC schemes, promote smart readiness integration, and address policy, technical, and social barriers in building performance assessment.

Sofia Bazzano from REHVA opened the conference by emphasizing the importance of collaborative innovation in achieving the European Green Deal goals. "Our mission is to align digital tools with regulatory ambitions and drive forward the next generation of EPCs," Bazzano noted, underlining REHVA's role as a bridge between research and policy.

Keynote Speeches: Policy and Funding Perspectives

The keynote session featured two prominent speakers:

- **Andrei Vladimir Litiu**, Director at EPB Center, provided an in-depth policy update. He elaborated on the 2024 EPBD recast and emphasized the need for national-level transposition by May 2026. The role of SmartLivingEPC and its sister projects in informing EU guidance documents and fostering cross-country collaboration was duly acknowledged.
- **Ulrike Nuscheler**, Senior Project Adviser at the European Climate, Infrastructure and Environment Executive Agency (CINEA) presented *"LIFE-CET 2025: Making buildings' renovation faster, deeper, affordable, smarter, service- and data-driven"*, emphasizing the importance of funding programs like LIFE-CET in accelerating building renovations and integrating smart technologies.

Project Presentations: Innovations in Practice

The event showcased the achievements of the three projects:

- **SmartLivingEPC**: Presented by Aggeliki Veliskaki from CERTH/ITI, the project introduced a comprehensive digital framework for energy performance certification, integrating Building Information Modeling (BIM), Internet of Things (IoT) technologies, and lifecycle assessment tools. The platform aims to provide enriched energy and sustainability-related information for both the design and actual performance of buildings.
- **CHRONICLE**: Manuela Freté from Smart Innovation Norway highlighted CHRONICLE's focus on user-centric tools and social innovation, demonstrating how digital solutions can enhance occupant engagement and comfort while improving energy performance.
- **SmarterEPC**: Sophie Dourlens-Quaranta of R2M Solution France discussed the project's approach to integrating Smart Readiness Indicators (SRI) with EPCs, utilizing a shared digital assessment hub and joint certification templates to streamline processes and support the implementation of the Energy Performance of Buildings Directive (EPBD).

Panel Discussion: The Role of Digital Tools

The panel discussion moderated by Pablo Carnero Melero, Secretary of REHVA's Technology and Research Committee, featured voices from national agencies, academia, and the private sector. It highlighted the urgency of aligning digital tool development with member state implementation needs, while addressing data accessibility, standardization, and end-user engagement.

Conclusion

The *SmartLivingEPC Final Event* underscored the critical role of digital innovation in transforming the building sector towards greater energy efficiency and sustainability. By fostering collaboration among stakeholders and showcasing cutting-edge tools, the event highlighted the potential of projects like SmartLivingEPC, CHRONICLE, and SmarterEPC to drive the EU's climate and energy goals forward.

As the EU transitions toward smarter, greener living, the groundwork laid by these projects will remain pivotal in achieving an integrated, digitally empowered built environment. ■

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REHVA News

Jarek Kurnitski SHASE International Honorary Member

REHVA Technology and Research Committee Chair Jarek Kurnitski was awarded with SHASE International Honorary Membership. The award was handed over by SHASE president prof. Takashi Akimoto in SHASE general assembly on May 15, 2025 in Tokyo. Next day Jarek Kurnitski was invited to give a public lecture in Nagoya City University on ZEB development trends in Europe. With this distinction SHASE recognised long and fruitful SHASE and REHVA cooperation where prof. Jarek Kurnitski has had a key role. REHVA and SHASE have been deeply involved in technical development related to zero emission and zero energy buildings where information exchange on best practices of both sides has been seen highly useful. Currently REHVA TRC and SHASE ZEB Committee are finalising a joint position document on ZEB development perspectives in EU and Japan. The joint position document and related case studies will be introduced in CLIMA 2025 REHVA-SHASE workshop in June in Milan. ■

The 2024 recast EPBD: What HVAC and building professionals need to know?

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Abstract

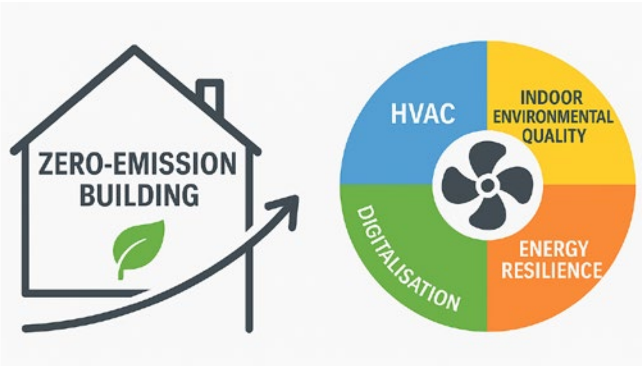
The **2024 recast of the Energy Performance of Buildings Directive (EPBD)** places **HVAC professionals** at the core of Europe's decarbonisation journey. No longer treated as peripheral, **heating, ventilation, and air-conditioning systems** are now central to achieving **zero-emission buildings**, improving **Indoor Environmental Quality (IEQ)**, and securing **energy resilience**. With this sharper regulatory focus comes an urgent demand for **fast**, **affordable**, and **flexible solutions**, qualities that the HVAC sector must deliver in both **new construction** and **renovation** contexts.

This article explores how the EPBD's new provisions, from **mandatory Building Automation and Control Systems (BACS)** and **self-regulating devices**, to **Minimum Energy Performance Standards (MEPS)** and **phase-outs of fossil fuel boilers**, are reshaping the profession.

Drawing on the final EPBD text and professional practice, it **outlines what HVAC actors must do to stay ahead by responding to the directive's ambition**, balancing concerns about feasibility with the business opportunity offered by the policy's clear direction. The message is clear: **those who adapt early will lead the transformation**. Those who don't risk being left behind.

Why the HVAC sector matters now more than ever

The 2024 recast of the Energy Performance of Buildings Directive (EPBD IV) is more than a technical update, it is the EU's answer to a cascade of overlapping crises. From **climate change** and **energy security** to **indoor health** and **social equity**, the revised directive reflects a broader, more urgent understanding of what buildings must deliver. And at the heart of that transformation lies the **performance of heating, ventilation, and air conditioning (HVAC) systems**.



The EPBD now links building energy performance not only to carbon targets, but to wider resilience goals: **protecting occupants' health**, **reducing fossil fuel dependency**, and **improving quality of life**, all while **accelerating renovation rates**. This shift places new responsibility, and opportunity, on HVAC professionals. Designers, installers, and maintenance experts are **no longer working behind the scenes**. Their decisions now influence whether a building meets zero-emission targets, delivers thermal comfort, and contributes to grid flexibility and digitalisation.

With new requirements for **smart controls**, **IEQ monitoring**, and **high-efficiency**, **low-temperature systems**, the EPBD outlines a new normal. The **HVAC sector is central** to this, not just because it represents a large share of building energy use, but because it holds the **technical key to making buildings truly perform**.

Fast, flexible, affordable: what the market needs now

The EPBD's ambition is clear, but success will hinge on whether the HVAC and construction sector can meet it with the speed, flexibility, and cost-efficiency demanded by the market. These three factors are emerging as the defining characteristics of next-generation building renovation and construction projects.

Speed is critical. With MEPS deadlines looming (e.g., phasing out G-class non-residential buildings by 2030), building owners and facility managers are under pressure to act quickly. HVAC solutions must be deployable with minimal disruption. **Prefabricated systems**, **modular HVAC units**, and **simplified commissioning** processes are gaining ground. Installers who can deliver **turnkey solutions**, especially in occupied buildings, will be highly sought after.

Flexibility refers to both system design and business models. The EPBD increasingly favours adaptable solutions: **heat pumps compatible with legacy emitters**, **hybrid ventilation systems**, and **interoperable BACS setups**. From a business standpoint, **leasing**, **performance contracting**, and **service-based offerings** (HVAC-as-a-Service) are becoming attractive options, especially for public sector clients facing budget constraints but bound by compliance timelines.

Affordability remains the top concern for both households and SMEs. Here, the HVAC sector can lead by offering **cost-effective staged renovation options**. The EPBD encourages this with renovation passports and EPC-linked recommendations, and **HVAC system upgrades** (e.g. zoning controls, smart thermostats, low-temperature emitters) often provide **high return-on-investment** even as **standalone measures**.

If the sector can respond with **practical**, **scalable**, and **customer-friendly** offerings, it will do more than **comply with policy**, it will drive the **energy transition** forward from the ground up.

HVAC sector concerns and response to the EPBD IV

As the HVAC sector digests the implications of the 2024 recast EPBD, a range of concerns have surfaced, particularly from SMEs, designers and installers, and industry associations. Yet alongside these concerns are signs of pragmatic adaptation and strategic alignment with the directive's ambitions.

Fossil fuel phase-out

One of the most pressing concerns is the gradual phase-out of fossil-fuel boilers. Article 13(7–8) pushes Member States to replace **stand-alone fossil fuel systems**, while Article 15 promotes financial incentives for switching to clean alternatives. Industry voices worry about the **feasibility of this shift**, especially in **poorly insulated buildings** or **rural areas** with legacy systems. Associations such as REHVA have stressed the need for a technology-inclusive and context-sensitive approach, allowing **hybrid systems** or **phased retrofits** where full electrification isn't yet viable.

In response, many manufacturers are fast-tracking **heat pump portfolios**, **hybrid-ready systems**, and **training programmes** for designers and installers. The message from policy is clear, and companies that provide clean, scalable, and serviceable solutions will be better placed as fossil-fuel phase-outs gain legal weight.

Building Automation and Control Systems (BACS)

BACS are no longer optional. Article 13 requires them in large buildings as of **2025** and **2029** depending on system size, and mandates smart features even in new residential buildings by **2026**. This has raised concerns among designers, installers and facilities teams about the **skills gap**, especially in smaller firms unaccustomed to advanced controls or IT integration.

In response, the sector is investing in **upskilling**, from manufacturer-led training to EU-funded initiatives under the LIFE and Horizon Europe programmes. Controls providers are also **simplifying interfaces** and offering **pre-configured solutions** to lower the barrier for entry. Interoperability and open protocols are becoming selling points, especially as **digital building logbooks** and **Smart Readiness Indicators (SRI)** begin to tie into broader compliance frameworks.

MEPS and EPCs

The move from voluntary recommendations to **mandatory energy upgrades** via MEPS (Minimum Energy Performance Standards) is perhaps the biggest paradigm shift. Many HVAC professionals welcome the visibility this gives to the renovation market, but stress the need for **clarity** and **consistency** in **national transpositions**, particularly regarding **EPC class thresholds** and exemption criteria.

To support clients, consultants and ESCOs are building **service offers** around **EPC improvement planning**, bundled with **funding advice** and **implementation support**. The new EPC requirements (Article 19), including advice on system temperatures, lifespan and low-carbon replacements, also present an opportunity for **HVAC experts** to position themselves as **trusted advisors**, not just contractors.

Indoor Environmental Quality (IEQ)

With Articles 13(4–5) and 9 now requiring **IEQ safeguards**, HVAC system design must address **ventilation**, **comfort**, and **air quality** as core deliverables, not side benefits. The industry's concern: how to balance IEQ with strict energy targets, especially in retrofits where space and budgets are limited.

The trend is toward integrated, performance-verified solutions, like demand-controlled ventilation with **CO_2 monitoring**, or **zoned heating/cooling** with **IEQ sensors**. Some manufacturers are beginning to **bundle IEQ** as part of system offerings, while associations like REHVA are updating guidance to support professionals in this dual-delivery model: energy savings + occupant wellbeing.

What professionals should do now

The 2024 recast EPBD marks a **shift** from performance on paper to **performance in operation**. For HVAC professionals, this means going beyond minimum compliance and proactively integrating **smarter**, **more resilient**, and **more user-focused solutions** into every phase of building design, installation, and maintenance.

Embrace the smart shift

The directive's digital backbone, encompassing **BACS**, the **Smart Readiness Indicator (SRI)**, and **Digital Building Logbooks (DBL)**, means that system performance will increasingly be monitored, recorded, and benchmarked in real time. This opens up space for data-driven services: **continuous commissioning**, **remote diagnostics**, and **predictive maintenance**. Controls engineers and HVAC specialists should anticipate demand for **interoperable systems**, **cloud-based dashboards**, and **user-friendly control interfaces**.

Professionals should also track the emerging SRI rollout. While currently voluntary, Article 15 signals that **large buildings** will likely require **SRI assessments from 2027**. Those with experience in building controls, automation and smart-grid-ready HVAC will be well-positioned to offer this as an **add-on service**.

Make IEQ visible

IEQ is no longer optional. As **sensors** become **mandated** in many new and renovated buildings, HVAC professionals will be expected to **specify**, **install**, and **interpret** IEQ **data**. Rather than treating this as **extra work**, it's a chance to demonstrate **added value**: delivering systems that don't just reduce energy use, but actively improve comfort, productivity, and health.

Professionals should align with standards such as **EN 16798** for IEQ parameters, and prepare to integrate **monitoring devices** (e.g. CO_2, RH, VOC sensors) into HVAC controls. This likely will be particularly relevant in schools, offices, and healthcare buildings.

Guide building owners through MEPS and EPC transitions

As MEPS deadlines approach, **building owners** will turn to **trusted professionals** to understand:

- Where they stand (via updated EPCs)
- What to do (via tailored improvement plans)
- And how to finance upgrades (via one-stop shops or subsidies)

HVAC professionals can lead this conversation. Article 19 requires EPCs to assess **heating system temperature regimes** and **replacement timelines**, turning every EPC into a potential project brief. With the right **training** and **digital tools**, HVAC companies can evolve from installers to **energy advisors**, packaging assessments, planning, and upgrades into an **integrated offer**.

Upskill, collaborate, and stay ahead

The directive encourages Member States to support **training** and **capacity building** (Article 17). HVAC professionals should proactively engage with these opportunities, especially in **digital skills**, **integrated system design**, and **low-carbon heat technologies** (e.g. heat pumps, district heating, hybrid systems). Crucially, as the focus shifts **from compliance to actual performance**, professionals must also take on **greater responsibility** and **long-term commitment** for delivering measurable outcomes. This evolution comes with a significant **challenge:** the **upskilling of trusted professionals**. For example, energy performance calculations that are still seasonal in many countries will soon need to **capture more complex indicators**, such as global warming potential. Achieving this **level of precision and consistency** can only be realistically supported through the adoption of **common EU-wide methodologies** and **tools**.

Cross-discipline collaboration is also essential. The EPBD requires HVAC professionals to work closely with architects, energy auditors, and digital service providers, not just to comply, but to deliver the **integrated building performance** Europe now demands.

Turning compliance into opportunity

The 2024 recast of the Energy Performance of Buildings Directive is not simply a regulatory burden, it's a **market signal**. It sets a clear direction for the decarbonisation of buildings, anchored in **measurable performance**, **smart digital integration**, and **occupant wellbeing**. For HVAC professionals, this represents both a challenge and a business opportunity.

Yes, the compliance bar is rising, but so is demand for **skilled experts** who can deliver real-world results. From system designers to controls integrators, from maintenance specialists to energy auditors, the sector is being called upon to **lead** the **transformation** of Europe's buildings.

Those who **act early**, by upskilling, offering **integrated solutions**, and helping clients navigate new requirements, will be in a **strong position**. The HVAC sector is no longer just about comfort or efficiency; it is central to achieving Europe's goals for energy security, climate neutrality, and health. And unlike in previous cycles of regulation, the EPBD IV creates a **continuous stream of projects** through MEPS, digitalisation mandates, and smart renovation tools.

Compliance is the baseline. Opportunity lies in **shaping what comes next**: a building stock that is **healthier, cleaner**, **smarter** and **better performing**. HVAC professionals are not just part of the process, they are now **key enablers of Europe's green transition**. ■

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