Health impact and building performance coupling: a virtual testbed for health-centric building system operation

Siu-Fung Fung[1], Volkan Doda[2], Ivan Korolija[1], Dejan Mumovic[1]
[1] UCL Institute for Environmental Design and Engineering, London, United Kingdom
[2] Atelier Ten London Limited, London, United Kingdom

Abstract

Airborne particulate matter deteriorates air quality in the built environment and contributes to a global burden of disease in terms of disability-adjusted life years (DALYs) loss. Active and passive building systems could improve indoor air quality by controlling contaminant concentrations in a building zone. However, existing environmental design and operational practices are often based on dynamic thermal model, which simulates building performance primarily through heat balance calculations without considering the epidemiological consequences of pollutant intake. This paper proposes a workflow to couple a chronic health impact model with EnergyPlus simulations, which enables the evaluation of building performance simultaneously from thermal and public health perspectives. After DALY loss in a notional non-domestic building in the UK is quantified, typical mechanical ventilation strategies are assessed. The adopted workflow can help built-environment professionals and stakeholders deliver high performance health-centric building system operations at all stages of a building's lifecycle.

Key Innovations

- Integration of an indoor air quality health impact model into a conventional building performance simulation workflow using EnergyPlus and Python.
- Assessment of various mechanical ventilation strategies and their effects on chronic health impact, energy use, and indoor air quality in the built environment.
- Quantification of the ingress of outdoor air contaminants into buildings and resulting tradeoffs among conflicting building performance parameters.

Practical Implications

Management of the temporal variation in contaminant concentration can improve long-term health outcomes for the building occupants and reduce building energy use.

Introduction

Indoor air quality (IAQ) is a pivotal aspect of building performance as it significantly impacts occupants' well-being and satisfaction with their environment. It substantially influences energy consumption, whereby the building sector accounted for 37% of energy use in 2023 (OECD, 2024). The heating, ventilating, and air conditioning (HVAC) systems are the major energy users in buildings that provide space conditioning and ventilation. Air pollutants, such as particulate matter 2.5 ($PM_{2.5}$), ozone (O_3), and nitrogen dioxide (NO_2), can be present in indoor environments due to anthropogenic activities and outdoor sources. Previous studies have shown that 65% of the particulate matter inhaled indoors originates from the outdoor environment (Fisk & Chan, 2017). Relevant authorities, such as the World Health Organization (WHO) (WHO, 2021), have recommended upper thresholds to limit exposure to air contaminants. These thresholds can be evaluated in relation to results from building performance simulation software to improve design proposals. Accordingly, design guidelines are available in various countries (ASHRAE, 2022; BSI, 2019; CIBSE, 2020). However, the adverse health outcomes due to variations in pollutant exposure are generally overlooked.

This knowledge gap can be bridged by leveraging domain knowledge in epidemiology. Health impact assessment (HIA) is a structured set of procedures, methods, and tools used to evaluate the health outcomes within a population and how these outcomes impact that population (WHO, 1999). To inform such assessment, WHO and the Global Burden of Disease (GBD) studies have been utilising Disability-Adjusted Life Years (DALYs) to quantify chronic health damage attributable to various risk factors across different countries since the 1990s. The loss of one DALY is interpreted as a year's loss of life due to premature mortality and living with a disability (Murray, 1994). According to the latest GBD study in 2021, particulate matter air pollution was the top environmental and occupational risk factor that incurred 8% of total DALY loss globally (Brauer et al., 2024). In the UK, a 20-day increase in life expectancy can be achieved by reducing annual mean $PM_{2.5}$ exposure by 1 ppm (COMEAP, 2010).

Soon after its development, DALY evolved into a common epidemiological metric for quantifying the chronic health impact of $PM_{2.5}$. Many studies have applied it in the built environment and the HVAC domain. Belias & Licina (2024) evaluated DALY and building energy using a shoebox model and highlighted the substantial contribution of indoor $PM_{2.5}$ originating from outdoors. Menacho et al. (2023) applied intake-based DALY, which is based on animal epidemiology studies, as part of the life cycle assessment in office buildings. Whilst surveys in residential settings are prevalent in this field (De Jonge et al., 2023; Fazli et al., 2021; Logue et

https://doi.org/10.26868/25222708.2025.1367

al., 2012), only limited application frameworks and case studies exist in non-domestic settings. The existing studies rely on the annual average concentrations in simple building energy models and not variable air pollutant concentrations in detailed models.

Therefore, this paper proposes a framework that quantifies building energy use and chronic health impacts attributable to air pollution dynamically and simultaneously starting from early building design stages, when design documentation is highly uncertain and limited, but the potential for improvement is the greatest. The outputs of the framework facilitate the evaluation of trade-offs among multiple conflicting performance criteria, such as building energy use, IAQ and chronic health impact. Beyond the design stages, the framework can also be applied to buildings in use for performance prediction and management during building operation.

Method

The overall research framework is shown in Figure 1 and consists of 4 stages. It leverages DesignBuilder (DesignBuilder Software Ltd, 2025) to establish the geometric model and detailed HVAC system configurations. These are then exported as input data files compatible with EnergyPlus (Crawley et al., 2001). EnergyPlus is advantageous as a free, open-source, physics-based whole building energy simulation software that undertakes validated dynamic thermal simulations. The input data file is finalised using eppy (Philip, 2020) to undergo dynamic thermal simulation with EnergyPlus Data Transfer API function "on begin zone timestep before set current weather". This implements control action and enables variable exchange in Python coupled with the health impact model. Data analysis and visualisation are performed using various Python packages (Harris et al., 2020; Python Software Foundation, 2023; The pandas development team, 2020).

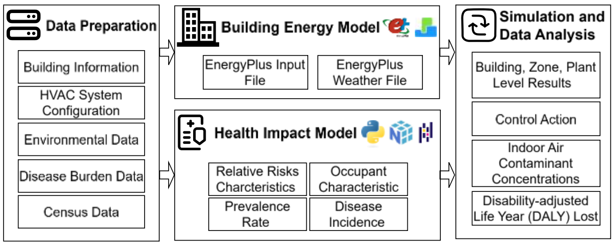

Figure 1: Overall research framework.

Building energy model

The proposed framework was applied to a hypothetical office building in Marylebone, London, United Kingdom (UK) to test its capabilities. A 3-zone typical office building model, as shown in Figure 2, was adopted from Korolija et al. (2013) as a representative example of the non-domestic building stock in the UK. This layout comprises office areas (Zone 1A and Zone 1B) and a communal area (Zone 2), whereby the former have higher occupancy density. The model's construction properties and environmental design settings comply with Building Regulations in England (HM Government, 2021b, 2021b, 2022), as summarised in Table 1. To reflect the recent climatic conditions around the adopted building site, hourly outdoor $PM_{2.5}$ concentration data for 2024 was retrieved from a government open dataset (Defra, 2025) whilst the weather file from Heathrow Airport was also updated from Meteostat (2025). The total number of occupants of each zone was derived from the occupant density of UK building regulation (HM Government, 2022), whilst its breakdown for each sex and age group was derived from the UK census 2021 dataset (Office for National Statistics, 2024). The occupant characteristics of each zone are shown in Figure 3. The choice of tenancy is arbitrary for illustrating the application of the framework. The ratio of males to females and the distribution of age groups vary depending on the zone. Zone 1A is assigned a population with a majority of female occupants, while Zone 1B is assigned a population with predominantly male occupants. In Zone 2, the proportion of male and female occupants is relatively balanced, although this population has a higher median age.

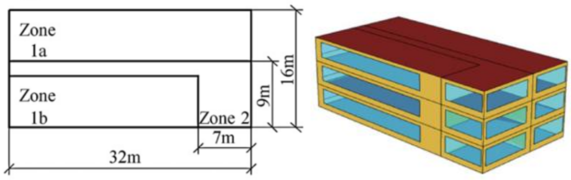

Figure 2: Archetype office building in the United Kingdom (Korolija et al., 2013).

Table 1: Building and occupants characteristics

Zone	1A	1B	2
Tenancy	Office 1	Office 2	Landlord common area
Occupant density	6 m^2/person		12 m^2 /person
Number of occupants	34.7	27.2	8.6
Median Age Group	35-39 years	35-39 years	40-44 years
Occupied hours	7:00-19:00, Monday to Friday		
Construction	Wall: 0.234 $W/m^2.^oK$ Window: 1.323 $W/m^2.^oK$ Window-to-wall Ratio = 50% Airtightness: $8m^3/h.m^2$ at 50Pa		
Heating	22 °C		20 °C
Cooling	24 °C		23 °C
Lighting	3.4 W/m^2.100lx		
Power	11.77W/m^2		

To limit the ingress of outdoor air contaminants during highly polluted hours of the year while providing ventilation to building zones, the baseline (Scenario 1) was established following Approved Document F (Part F) of the UK Building Regulations (HM Government, 2021a). This provided the legally required outdoor air to the building during all occupied hours based on the design

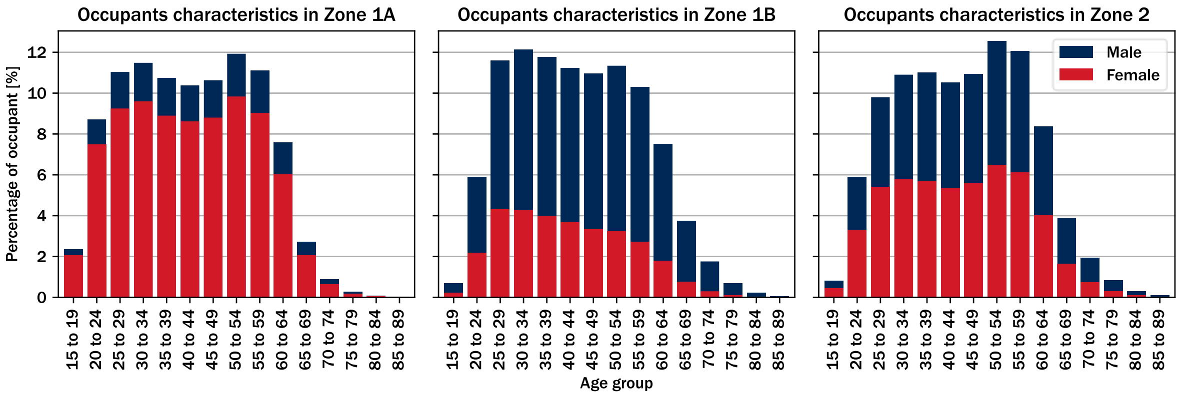

Figure 3: Occupants' characteristics derived from industry sector census in UK (Office for National Statistics, 2024)

occupancy. Scenarios 2, 3, and 4 were then used to implement the Carbon dioxide (CO_2)-based indoor air quality procedure (IAQP), which determines the outdoor air flow rate required to maintain a defined contaminant setpoint using mass balance equations (ASHRAE, 2022). While scenario 2 permitted a full supply of outdoor air, in scenarios 3 and 4, the maximum outdoor air fraction was limited to 0.5 and 0, respectively, when the outdoor $PM_{2.5}$ concentration exceeded the zone mean. Filtration of $PM_{2.5}$ was omitted from the AHUs and fan coil units. The ambient and target setpoint CO_2 were 400 and 800 ppm, respectively (BSI, 2019; HM Government, 2021a).

The HVAC system that conditioned all building areas to meet the environmental design criteria specified in Table 1 was designed as an air-water system. Capacities of the major HVAC equipment shown in Table 2 were sized automatically based on design weather days in EnergyPlus. An electric chiller and gas-fired boiler supplied chilled water and hot water to the fan coil units in each zone. They also served the air handling unit (AHU), which delivered fresh air and handled the ventilation demand of all building zones.

Table 2: Sizes and design conditions of major HVAC plants

HVAC System	Scenario 1	Scenario 2, 3 and 4
Air Distribution System	AHU Supply Air Flow Rate: 705.5 L/s	AHU Supply Air Flow Rate: 666.0 L/s
Chiller Water System	Chiller Capacity: 46.38 kW	Chiller Capacity: 45.63 kW
	Supply Water Temperature: 6°C Return Water Temperature: 10°C	
Hot Water System	Boiler Capacity: 44.60 kW	Boiler Capacity: 42.10 kW
	Supply Water Temperature: 80°C Return Water Temperature: 70°C	

Quantitative health impact model

The health impact model was developed based on disease burden data from the GBD study 2019 (Global Burden of Disease Collaborative Network, 2021, 2024), which documented the prevalence rate (y_0), incidence rate (IND), DALY loss, and relative risk characteristics curves due to $PM_{2.5}$ exposure in various countries, including the UK. It is organised by sex, age group, and health outcomes. The detailed pre-processing and application workflow for incidence-based DALY calculations adopted in this study have been developed in De Jonge & Laverge (2022); Fung et al. (2024) and Logue et al. (2012) that were adopted in this study. The examined chronic health outcomes concerning ambient particulate matter pollution include chronic obstructive pulmonary disease, type 2 diabetes, ischaemic heart disease, lower respiratory infections, lung cancer, and stroke. Figure 4 illustrates the log-linear changes in mean relative risk (RR) for each of these outcomes in relation to $PM_{2.5}$ concentration. An RR of 1.0 indicates that the risk of achieving a specific health outcome with the given risk factor is equivalent for those exposed to it who are not subjected to the same risk.

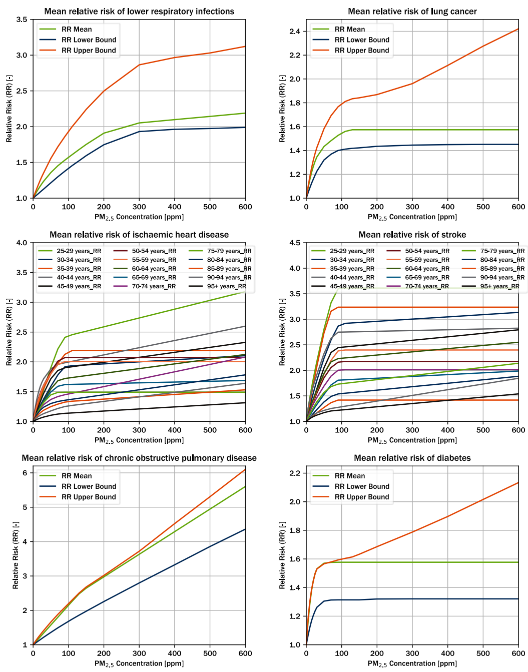

Figure 4: Mean relative risk of selected chronic health outcomes (Global Burden of Disease Collaborative Network, 2021)

Equation 1 shows the adopted step-function quantifying DALY loss for a time differential (Δt). For each of the health outcomes, sex, and age group, the concentration-

https://doi.org/10.26868/25222708.2025.1367

response coefficient (β), indoor $PM_{2.5}$ concentration (c) and prevalence rate (y_0) inform the number of incidence cases of an outcome over the period Δt, which is set to be 1 hour in this study. The damage factor (ΔDALY/ΔINC) converts the incidence rate and number of occupants (N) across various age groups into DALYs lost as the output. Hence, this model was applied separately to different health outcomes, building zones, occupant sexes, and numbers of occupants in various age groups.

$$\Delta DALY[c(t)] = \frac{\Delta DALY}{\Delta INC} \cdot \Delta INC[c(t)]$$

$$= \frac{\Delta DALY}{\Delta INC}\{N y_o \sum [1 - \exp(-\beta(RR, c(t)) \cdot c(t))] \Delta t\} \quad (1)$$

Result

This section presents the energy performance, IAQ, and chronic health impacts for all scenarios during a typical winter week (20–26 January), a typical summer week (30 June–6 July), and throughout the evaluated year.

Overall energy performance

Figure 5 illustrates the breakdown of annual energy use intensity by end-use. Scenario 1's total energy use (99.03 kWh/m^2) is the highest among all scenarios, and an 18.8% reduction is achieved by applying demand-controlled ventilation (DCV), which adjusts the fraction of outdoor air based on CO_2 and $PM_{2.5}$ concentration in Scenario 4. The auxiliary energy consumption does not change notably between Scenarios 2, 3 and 4 because the current workflow does not vary fan power in response to the implemented $PM_{2.5}$-based flow rate controls. Significant further energy use reduction is expected when this is captured in the future. The energy used for heating and cooling generally decreases and increases, respectively, as the outdoor air supply diminishes. Energy use for lighting and equipment remains constant across all scenarios.

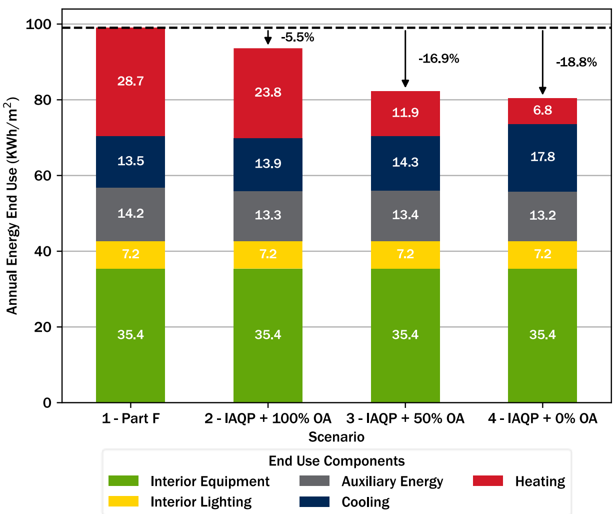

Figure 5: Breakdown of annual energy end use.

Major building services equipment's performance

The primary intervention implemented in Scenarios 3 and 4 reduces the maximum outdoor air (OA) fraction from 1.0 to 0.5 and 0.0, respectively, when the outdoor $PM_{2.5}$ concentration exceeds the zone mean concentration. Otherwise, the fraction is maintained at 1.0 and follows the CO2-based IAQP. The OA fraction is overlaid in the relevant graphs on the next page, plotted against the secondary axis to highlight the control action for outside air delivery.

Table 5 compares the energy consumption of major HVAC equipment for the entire year. Figure 6 illustrates the boiler heating rate over a typical winter week, during which the rates for Scenarios 1 and 2 are consistently higher and the boiler is running continuously during occupied hours. The intermittent reduction of OA fraction in Scenarios 3 and 4 decreases annual boiler energy consumption by 76% when comparing Scenario 4 to Scenario 1. A 13% reduction in fan energy use was also observed. This is attributed to CO_2-based IAQP as no further significant changes are observed between Scenarios 2, 3 and 4. In contrast, Figure 7 shows the chiller electricity rate during a typical summer week, whereby the chiller in Scenario 4 consumes more energy than the other scenarios, with a 32% increase compared to Scenario 1. This is because outdoor air provides free cooling, and the reduced OA fraction in Scenario 4 limits this benefit, hence increasing chiller energy use.

Table 5: Energy consumption [kWh] for major HVAC plant equipment with comparison to baseline

Scenario	Boiler	Chiller	Supply or Return Fan
1	13265	6417	1875
2	11017 (-17%)	6597 (+3%)	1666 (-11%)
3	5509 (-58%)	6812 (+6%)	1694 (-10%)
4	3143 (-76%)	8462 (+32%)	1624 (-13%)

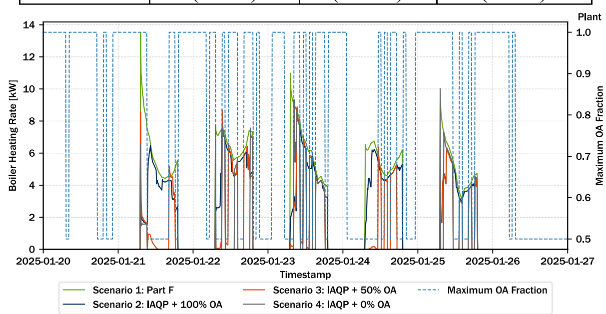

Figure 6: Boiler heating rate during a typical winter week.

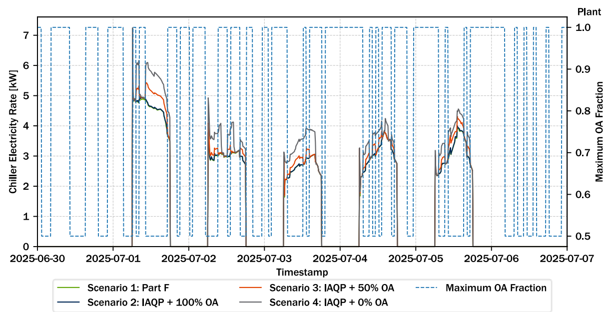

Figure 7: Chiller electricity rate during a typical summer week.

https://doi.org/10.26868/25222708.2025.1367

Indoor air quality and ventilation system operation

As shown in Table 3, the annual mean outdoor and Scenario 1 indoor $PM_{2.5}$ concentrations are 10.59 and 10.88 ppm, respectively. Scenario 4 reduces the annual mean concentration by 16% compared to Scenario 1. The mean concentrations during the typical winter week are consistently higher than those for the typical summer week across all scenarios. To delineate the characteristics during bad outdoor conditions, the results for a typical winter week in zone 1B are presented in Figure 8. This figure illustrates the temporal characteristics of air pollutant concentrations and the corresponding building system operation.

Table 3: Outdoor and mean indoor $PM_{2.5}$ concentrations [ppm] compared to baseline

Period		Winter Typical Week	Summer Typical Week	Full Year
Outdoor		11.89	8.94	10.59
Scenario	1	12.81	9.28	10.88
	2	12.79 (-0.1%)	9.29 (0.1%)	10.85 (-0.2%)
	3	12.42 (-3.0%)	8.96 (-3.5%)	10.49 (-3.6%)
	4	11.13 (-13%)	7.96 (-14%)	9.18 (-16%)

The zone $PM_{2.5}$ concentration for Scenario 1 is the highest among all scenarios at all times, and subsequent scenarios achieve incremental reduction. On 24 January, the outdoor air is heavily polluted throughout the morning, which reduces the outdoor air fraction in Scenarios 3 and 4. The rate of change of indoor concentration decreases following the outdoor air fraction as the mechanical ventilation flow rate is reduced. On this date, the outdoor conditions improve in the afternoon when the supply of outdoor air starts diluting the indoor $PM_{2.5}$ concentration.

This trend reverses for zone CO_2 concentration. Scenario 4 yields the worst conditions on 21 and 24 January, with CO_2 concentration rising up to 2749 ppm. Even though this does not exceed the threshold set by occupational safety standards, it is unlikely to be acceptable due to its adverse effect on cognitive functions. The CO_2 concentration rises sharply from Scenario 3 to 4, suggesting that the optimal minimum OA fraction is likely to be between 0.0 and 0.5.

Chronic health impact incurred

Hourly DALY loss accumulates during occupied hours at the zone level, with the total losses calculated separately for each age group and sex. For instance, Figure 9 depicts the DALY loss incurred during a typical winter week in Zone 1B. The maximum loss occurs on the afternoon of 24 January, coinciding with the previously mentioned zonal IAQ result. The reduction of outdoor air fraction also reduces this loss. Likewise, the annual cumulative loss for each zone occupant group is summarised in Table 4, which indicates a 15-16% reduction in DALY loss compared to Scenario 1. This result is also normalised according to the number of occupants in the individual building zone, as shown in Table 5. Depending on the

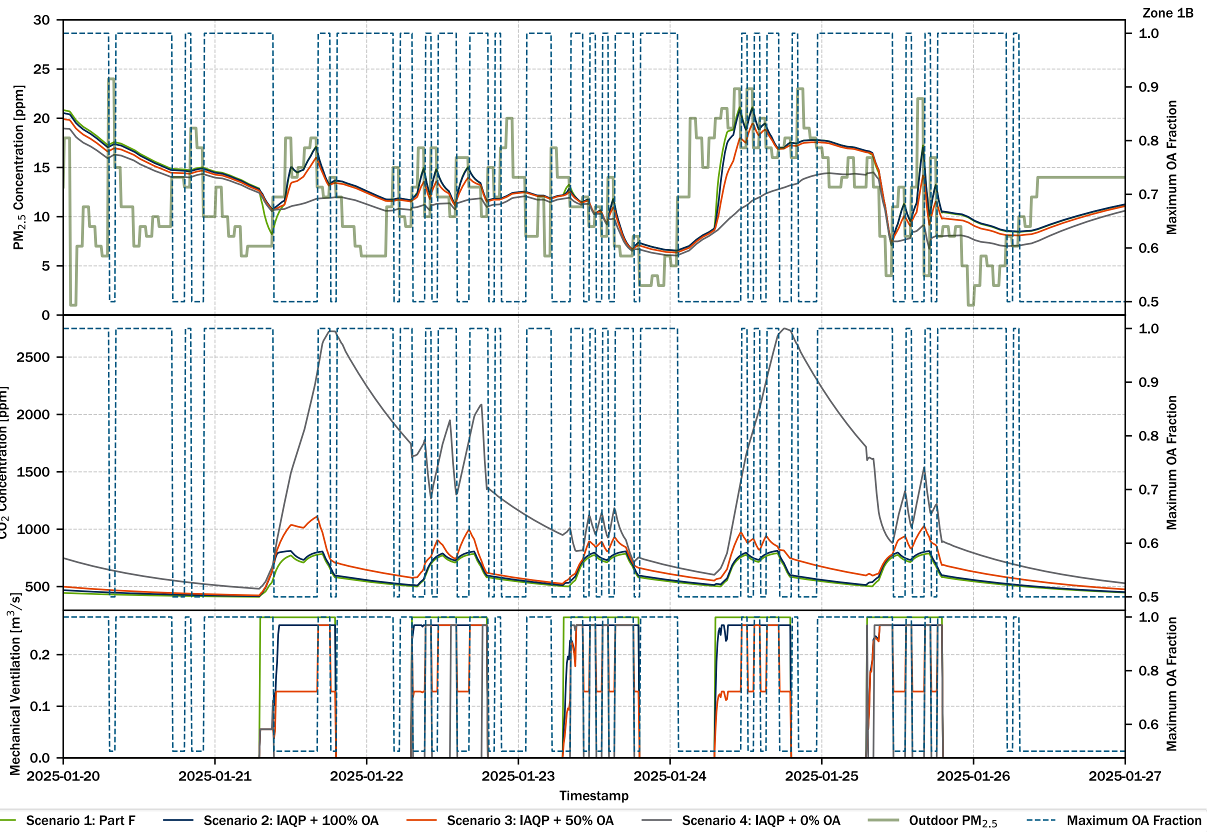

Figure 8: Air pollutant concentrations, mechanical ventilation rate, and maximum outdoor air fraction in Zone 1B during a typical winter week.

https://doi.org/10.26868/25222708.2025.1367

scenario, up to 10 days of DALY loss is incurred by an occupant exposed to full year of high indoor $PM_{2.5}$ concentration.

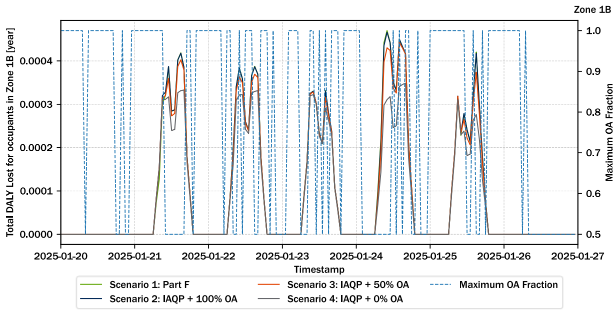

Figure 9: DALY loss incurred during a typical winter week in Zone 1B

Table 4: Cumulative DALY loss per building zone.

Scenario	Zone 1A	Zone 1B	Zone 2
1	0.5924	0.6997	0.2279
2	0.5936 (+0.21%)	0.7013 (+0.22%)	0.2282 (+0.13%)
3	0.5734 (-3.2%)	0.6768 (-3.3%)	0.2209 (-3.1%)
4	0.4986 (-16%)	0.5880 (-16%)	0.1947 (-15%)

Table 5: DALY loss in equivalent days per occupant of the building zone.

Scenario	Zone 1A	Zone 1B	Zone 2
1	6.226	9.379	9.680
2	6.239	9.400	9.693
3	6.027	9.072	9.383
4	5.241	7.882	8.273

Discussion

The energy use of the building and its HVAC equipment decreases as the scenario iteration progresses. Because changes in auxiliary energy use are not fully captured, heating and cooling energy are the primary variables as the outside air fraction supply rate changes. For example, the heating demand reduces as the outdoor air fraction decreases because the cool air introduced into the building zone diminishes. This reduces heating demand from the zone fan coil units, which is not overridden by the controls implemented in this study. Similarly, during the summer, heat gains from occupant activities and heat gains through the building envelope increase the demand for cooling. In scenarios with high outdoor air fraction, some of this demand is met passively via the supply of cooler outdoor air. Therefore, the cooling energy use increases as the outdoor air supply is constrained from Scenario 1 towards Scenario 4. As the outdoor air fraction was adjusted independently from AHU controls, the auxiliary energy use mostly remained unchanged irrespective of the scenario, except for the change due to the introduction of DCV from Scenario 2 onwards.

With regards to indoor air quality, this study confirms that the maximum outdoor air fraction reduction, depending on outdoor and indoor environmental conditions, can dynamically reduce the indoor $PM_{2.5}$ concentration. Although Scenario 4 entirely restricts the mechanical outdoor air supply at times of poor outdoor air quality, the resulting indoor $PM_{2.5}$ concentration still increases during polluted hours. This is attributed to the infiltration of outdoor pollutants through the building fabric. Considering CO_2 as the proxy for ventilation effectiveness, the indoor concentration level was maintained below the defined setpoint concentration (800 ppm) in Scenarios 1 and 2. With the forced reduction of outdoor air fraction to limit $PM_{2.5}$ exposure in Scenarios 3 and 4, the CO_2 concentration grows rapidly but remains below the hazardous thresholds in the UK, defined as 5,000 ppm for an 8-hour average period and 15,000 ppm for a 15-minute average period (The Stationery Office, 2011). Outside of occupied hours, provision of fresh air reactivates, demonstrating the opportunity to harvest clean air from the outdoors to dilute the indoor air before the next period of occupation. The effectiveness of this purge mode can be improved further by increasing flow rates during unoccupied hours. This can be modelled, optimised and scaled up in future works.

With regards to the $PM_{2.5}$ concentration, chronic health impacts can be mitigated by reducing the intake of outdoor air pollutants. Following Equation 1, as the $PM_{2.5}$ concentration decreases, the incidence of RR reduces, resulting in an overall reduction of DALY as output. However, Table 7 shows that the annual loss per person for occupants in Zone 1B and Zone 2 are similar to and higher than in Zone 1A. Such disproportionality is due to the characteristics of the occupant population. Figure 3 illustrates that occupants in Zone 1A are relatively young and predominantly female, which coincides with lower prevalence and relative risk. In contrast, the population in Zone 2 is comparatively older and suffers substantial losses per occupant, which is comparable to those in Zone 1B, which has a predominantly male population. This result highlights that the same environmental design criteria and operation characteristics could lead to different physiological responses for occupants of various sexes and ages and knowledge of occupant population groups is important for optimal control.

The health impact result is comparable to previous population-based studies. Comparing Zone 1B in Scenarios 1 and 3 as an example, the mean $PM_{2.5}$ concentration reduces by 0.39 ppm. This results in a corresponding reduction of 0.3 days in DALY per year of exposure. The lifetime age-adjusted DALY loss incurred by an average person exposed to such variation for the whole career life (i.e. approximately 37 years for Europeans) is 11.1 days. This is similar at scale and lower than the approximate 20-day life expectancy gain per 1 ppm annual exposure reduction (COMEAP, 2010), as it accounts for the whole life of a person.

The monetary value of DALY loss varies greatly and remains an emerging area in public health. In the UK context, reducing DALY by 1 could be approximated as a gain of 1 Quality Adjusted Life Year, which is clinically worth £20,000-30,000 (Appleby et al., 2007). In the future, this could be included as part of a cost function that considers cost of building energy and occupant health impacts.

This study expands the understanding of building services system operation from the public health perspective, which can aid in health-centric building system design and operation using quantitative HIA with epidemiological metrics. The proposed framework can be applied in the planning process that evaluates chronic health outcomes of various design options and available occupant information. This framework could also be utilised for existing buildings to evaluate retrofitting options, routine adjustment of building automation control, and long-term HIA interventions. In the next phase of this research, the current framework will be applied to different building types and HVAC system configurations to continue exploring the nexus of building performance and health impact. The indoor contaminant source generation and removal will be modelled to enrich the building energy model and improve the operation of technical building systems informed by chronic health impact model. Various rule-based and receding-horizon control strategies that integrate health and energy models will be formulated to limit the health impact within a definite time horizon by modulating setpoints of contaminant concentration and various parts of HVAC system components. This will facilitate the ongoing development of building performance digital twins that improve building design, operation, and health outcomes distributed to the population of the building concerned.

Conclusion

This paper presents a new workflow towards health-centric building system operation for non-domestic buildings. The aim is to expand the understanding and application of building performance simulation from a public health and epidemiology viewpoint, focusing on outdoor and indoor air quality issues. A framework is proposed to couple the chronic health impact model with the EnergyPlus simulation, which dynamically assesses chronic health outcomes using DALY and other metrics related to IAQ and building energy use. A hypothetical mechanically ventilated notional office building in London, UK was modelled with diversified tenancy and outdoor environmental conditions informed by public datasets. The results demonstrate that a 16% reduction in adverse health outcomes over the long term is achievable by limiting the ingress of outdoor air pollutants via mechanical ventilation. However, conflicting needs among energy use of major HVAC plants, good IAQ and DALY loss of different occupant groups are discussed by considering various simulation periods. These compromises should be considered to inform future development of design and control strategies in building automation systems, especially when the outdoor environment is highly polluted.

Nomenclature

AHU	Air Handling Unit
CO_2	Carbon Dioxide
DALY	Disability-Adjusted Life Year
GBD	Global Burden of Disease
HIA	Health Impact Assessment
HVAC	Heating, Ventilating, and Air Conditioning
IAQ	Indoor Air Quality
IAQP	Indoor Air Quality Procedure
OA	Outdoor Air
$PM_{2.5}$	Particulate Matter 2.5
RR	Relative Risk

Acknowledgement

This work was supported by The Engineering and Physical Sciences Research Council (EPSRC DTP Grant Reference: EP/W524335/1) and Atelier Ten London Limited as the industrial sponsor.

References

Appleby, J., Devlin, N., & Parkin, D. (2007). NICE's cost effectiveness threshold. *BMJ : British Medical Journal*, *335*(7616), 358–359. https://doi.org/10.1136/bmj.39308.560069.BE

ASHRAE. (2022). *ANSI/ASHRAE Standard 62.1-2022 Ventilation and Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Brauer, M., Roth, G. A., Aravkin, A. Y., Zheng, P., Abate, K. H., Abate, Y. H., Abbafati, C., Abbasgholizadeh, R., Abbasi, M. A., Abbasian, M., Abbasifard, M., Abbasi-Kangevari, M., ElHafeez, S. A., Abd-Elsalam, S., Abdi, P., Abdollahi, M., Abdoun, M., Abdulah, D. M., Abdullahi, A., … Gakidou, E. (2024). Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021. *The Lancet*, *403*(10440), 2162–2203. https://doi.org/10.1016/S0140-6736(24)00933-4

BSI. (2019). *BS EN 16798-1:2019: Energy performance of buildings - ventilation for buildings - Part 1 : indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - module M1-6*.

CIBSE. (2020). *Health and wellbeing in building services: CIBSE TM40*. Chartered Institution of Building Services Engineers.

COMEAP. (2010). *The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/304641/COMEAP_mortality_effects_of_long_term_exposure.pdf

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., Strand, R. K., Liesen, R. J., Fisher, D. E., Witte, M. J., & Glazer, J. (2001). EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings*, *33*(4), 319–331. https://doi.org/10.1016/S0378-7788(00)00114-6

De Jonge, K., Ghijsels, J., & Laverge, J. (2023). Energy savings and exposure to VOCs of different household sizes for three residential smart ventilation systems with heat recovery. *Energy and Buildings*, *290*, 113091. https://doi.org/10.1016/j.enbuild.2023.113091

De Jonge, K., & Laverge, J. (2022). Time-resolved dynamic disability adjusted life-years estimation. *Indoor Air*, *32*(11), e13149. https://doi.org/10.1111/ina.13149

Defra. (2025). *Data Archive- Defra, UK* (UK; United Kingdom) [Dataset]. Department for Environment, Food and Rural Affairs (Defra), Nobel House, 17 Smith Square, London SW1P 3JR helpline@defra.gsi.gov.uk. https://uk-air.defra.gov.uk/data/

DesignBuilder Software Ltd. (2025). *DesignBuilder Software Ltd—Home* [Computer software]. https://designbuilder.co.uk/

Fazli, T., Dong, X., Fu, J., & Stephens, B. (2021). Predicting US Residential Building Energy Use and Indoor Pollutant Exposures in the Mid-21st Century. *ENVIRONMENTAL SCIENCE & TECHNOLOGY*, *55*(5), 3219–3228. https://doi.org/10.1021/acs.est.0c06308

Fisk, W. J., & Chan, W. R. (2017). Effectiveness and cost of reducing particle-related mortality with particle filtration. *Indoor Air*, *27*(5), 909–920. https://doi.org/10.1111/ina.12371

Fung, A. S.-F., Doda, V., Korolija, I., & Mumovic, D. (2024). Optimising Health Impact at the Building Level: The Development of a Methodology. *CIBSE Technical Symposium 2024*.

Global Burden of Disease Collaborative Network. (2021). *Global Burden of Disease Study 2019 (GBD 2019) Particulate Matter Risk Curves* [Dataset]. Institute for Health Metrics and Evaluation (IHME). https://doi.org/10.6069/KHWH-2703

Global Burden of Disease Collaborative Network. (2024). *Global Burden of Disease Study 2019 (GBD 2019) Data Resources | GHDx*. https://ghdx.healthdata.org/gbd-2019

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

HM Government. (2021a). *The Building Regulations 2010. Approved document F, Ventilation. Volume 2, Buildings other than dwellings*.

HM Government. (2021b). *The Building Regulations 2010. Approved document L, Conservation of fuel and power. Volume 2, Buildings other than dwellings*.

HM Government. (2022). *The Building Regulations 2010. Approved document B, Fire safety. Volume 2, Buildings other than dwellings*. https://assets.publishing.service.gov.uk/media/639ae876e90e0721839ea637/Approved_Document_B__fire_safety__volume_2_-_Buildings_other_than_dwellings__2019_edition_incorporating_2020_and_2022_amendments.pdf

Korolija, I., Marjanovic-Halburd, L., Zhang, Y., & Hanby, V. I. (2013). UK office buildings archetypal model as methodological approach in development of regression models for predicting building energy consumption from heating and cooling demands. *Energy and Buildings*, *60*, 152–162. https://doi.org/10.1016/j.enbuild.2012.12.032

Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2012). A method to estimate the chronic health impact of air pollutants in U.S. residences. *Environmental Health Perspectives*, *120*(2), 216–222. https://doi.org/10.1289/ehp.1104035

Meteostat. (2025). *Meteostat Developers* [Dataset]. https://dev.meteostat.net/

Murray, C. J. (1994). Quantifying the burden of disease: The technical basis for disability-adjusted life years. *Bulletin of the World Health Organization*, *72*(3), 429–445.

OECD. (2024). *World Energy Outlook 2024*. IEA Publications. https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf

Office for National Statistics. (2024). *Industry—Census 2021* [Dataset]. https://www.ons.gov.uk/datasets/TS060/editions/2021/versions/5

Philip, S. (2020). *Eppy* [Computer software]. https://eppy.readthedocs.io/en/latest/

Python Software Foundation. (2023). *Python* [Computer software]. https://www.python.org/

The pandas development team. (2020). *pandas-dev/pandas: Pandas* [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.3509134

The Stationery Office. (2011). *EH40/2005 workplace exposure limits: Containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations (as amended)* (2nd ed). HSE Books.

WHO. (1999). *Health Impact Assessment: Main concepts and suggested approach*. World Health Organization. http://www.euro.who.int/document/PAE/Gothenburgpaper.pdf

WHO. (2021). *WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. https://www.who.int/publications-detail-redirect/9789240034228