Advancing a health-model linked smart control framework to improve occupant health and comfort in residences

Elizabeth Cooper [a], *Yan* Wang [a], *Samuel* Stamp [a], *Dejan* Mumovic [a]

[a] Institute for Environmental Design & Engineering, Bartlett School of Environment Energy & Resources, University College London, London, UK, elizabeth.l.cooper@ucl.ac.uk.

Abstract. Evidence for the impact on health of interventions that improve the indoor environment can take years or even decades to be identified and actionable. However, health impact modelling can be used to estimate changes in rates of morbidity and mortality due to changes to the environment, which can be simulated using physics-based models. In the past, these tools have not been used in combination to assist in real-time building controls. The work described here builds upon previous work that proposed a smart control framework that combined portable air purifiers and automatic window control systems to reduce indoor $PM_{2.5}$ concentrations in residences whilst maintaining thermal comfort. The modelled changes can inform health models for better estimations of the impacts to population health due to the implementation of controls that use both thermal conditions and contaminant concentrations as control targets. The IAQ modelling, which uses EnergyPlus to simulate both indoor contaminants and thermal conditions, includes different ambient pollution levels, and, importantly, different occupant behaviour profiles (e.g., cigarette smoking). The approach to quantitative health impact assessment in this work is through life-table models that predict survival patterns based on age-specific mortality figures and hazard ratios. The simulation results showed that dual control of portable home air purifiers and window openings has the potential to not only maintain thermal comfort but also achieve effective $PM_{2.5}$ removal even in cases of high indoor sources which, consequently, can lead to considerable health benefits at a relatively low energy cost.

Keywords. Smart building controls, health modelling, air purifiers, automated window operation.

1. Introduction

Recent decades have seen considerable research efforts focused on measures to improve indoor air quality (IAQ) without sacrificing energy efficiency (e.g., Ji et al., 2020; Kosar & Novosel, 2006). The most common component of indoor air used in ventilation control strategies, both in research and practice, is carbon dioxide (CO_2) (Chenari et al., 2016). However, it is not an accurate proxy for all indoor air pollutants, in particular non-gaseous pollutants such as particulate matter (PM). PM refers to a blend of airborne liquid droplets and solid particles and is categorised as PM_1, $PM_{2.5}$ and PM_{10} based on aerodynamic diameter. $PM_{2.5}$ has been extensively researched in both outdoor and indoor air as it can infiltrate deep into the respiratory system, causing severe health problems including cardiovascular diseases and asthma (Fan et al., 2016; Pope III et al., 2020). It has been generally accepted that there is a link between exposure to $PM_{2.5}$ and an increase in all-cause mortality (Pope et al., 2020). Thus, reductions in $PM_{2.5}$ are estimated to have major health benefits (Schraufnagel et al., 2019).

Portable home air purifiers (HAPs) that use high-efficiency particulate air (HEPA) filters have been demonstrated to be effective at reducing indoor $PM_{2.5}$ concentrations with a low energy cost (Fisk, 2018). Noticeably, a new generation of HAPs (such as those used in a recent study (Cooper et al., 2021a)) employ built-in $PM_{2.5}$ sensors and can be connected to the internet to realise instant remote control, providing an opportunity to be part of an advanced automation system. Another critical part of controlling the indoor environment in residences is window opening, and implementing automatic window control systems holds promise as a building control strategy, (Fiorentini et al., 2019; Psomas, Fiorentini, et al., 2017; Psomas, Heiselberg, et al., 2017) (Stazi et al., 2017).

Despite its known negative health effects and the availability of sensor technologies, $PM_{2.5}$ has rarely been used as an indicator of IAQ in building controls. In one of examples found, An et al. (2021) developed an automatic window control system to mitigate indoor $PM_{2.5}$. However, when outdoor air quality is as poor as or worse than indoors, this approach is ineffective. In this regard, the addition of an air cleaning technology to the window control system makes it more resilient and adaptable.

This paper builds on previous work that described a window control framework that integrated HAPs and automatic window systems to reduce indoor PM2.5 concentrations and maintain thermal comfort (Wang et al., 2022). The control framework was initially tested through a simulation-based case study of a modern 1-bedroom apartment in London, UK. In the previous work, the indoor source of PM2.5 was confined to cooking, and the range of outdoor concentrations was limited. The originality of the work presented here is the introduction of additional complexity through a range of realistic occupant behaviours and variable outdoor conditions. Specifically, cigarette smoking and candle burning have been added to the testing models, and two new outdoor PM2.5 profiles have been simulated. Cigarette smoking, despite changes in public acceptance and known health risks, remains a common behaviour in the UK and throughout Europe. According to the UK Office for National Statistics, 13.3% of adults in the UK, or about 6.6 million people, smoke cigarettes(ONS, 2022). Whilst in the EU in 2019 18.4% of people aged 15 and older were daily smokers (Eurostat, 2022). While bans on indoor smoking in public buildings are widespread, smoking indoors remains common in homes. Another behaviour common in European homes (Bekö et al., 2013)as a source of PM2.5 is the burning of candles. It is these two behaviours, therefore, that are simulated in the work presented here.

2. Methods

2.1 Case study description

The case study residence is a one-bedroom (51 m^2) flat located on the 9th floor of a high-rise building near two heavily trafficked roads in London, UK. The building was constructed in 2015 and relies on natural ventilation without mechanical cooling. Details of the environmental monitoring can be found in previously published work (Cooper et al., 2021b; Wang et al., 2022).

EnergyPlus 9.4 was chosen as the simulation software, as it has been previously validated in simulations of indoor pollutants and thermal environment (Taylor et al., 2014). The occupants' cooking behaviour (e.g., type of cooking, use of extract hood, etc.) was reported in interviews and was used to develop the simulation schedules and emission rates. The model was tested against the measured data and found to have good fidelity (e.g., mean bias error for $PM_{2.5}$ = 0.68μg/m³, and for indoor temperature 0.6 °c).

2.2 Simulation Scenarios and control strategies

Four scenarios were designed to simulate a range of indoor air quality conditions that might commonly be found in homes in the UK and the EU, a summary of which can be found in **Table 1**. Two different weeks were simulated that included outdoor $PM_{2.5}$ concentrations that were, compared to mean London levels, relatively high (mean 16 μg/m³ range 0-68.3 μg/m³) and relatively low (mean 5 μg/m³ range 0-10.9 μg/m³), but with similar outdoor temperatures.

Table 1

Summary of the four scenarios modelled. All scenarios used the same emission rate and schedule for cooking. Outdoor $PM_{2.5}$ data were sourced from Greenwich-John Harrison May station of the London Air Quality Network (https://www.londonair.org.uk/LondonAir)

	Outdoor $PM_{2.5}$	Indoor $PM_{2.5}$ Source	Emission Rate (mg/min)
Scenario 1 (S1)	Relatively High (22-29 Aug)	Ciga-rette Smok-ing	0.99 (Hu et al., 2012)
Scenario 2 (S2)	Relatively Low (14-21 Aug)		
Scenario 3(S3)	Relatively High (22-29 Aug)	Candle Burning	0.25 (Hu et al., 2012)
Scenario 4 (S4)	Relatively Low (14-21 Aug)		

Cooking schedules and emission rates were the same as those used in previous work (Shrubsole et al., 2012; Wang et al., 2022).

2.3 Health impact assessment

Estimations of the impact of interventions which change exposures to environmental hazards on population morbidity and mortality can be achieved through quantitative health impact assessments. The approach used in this work was life-table models which predict survival patterns based on changes in age-specific death rates (Miller & Hurley, 2003). In the work presented here, life-table models were used to quantify the impacts on mortality from reductions in indoor $PM_{2.5}$ concentrations. Formulae from Miller and Hurley were the basis for the calculation of changes in mortality and life expectancy (Miller & Hurley, 2003; Miller, 2010) and were implemented with the open-source statistical software R (R Core Team, 2018).

For the modelling presented here the occupants were estimated to spend 7 hours per day in the room in which the air purifier and automated windows were located. Data for population and age-specific mortality data were taken from the UK Office for National Statistics 2019 reports. All-cause and disease-specific relative risk associated with exposure to $PM_{2.5}$ were taken from the 2019 Global Burden of Disease study (WHO, 2020). Additional background, uncertainty analysis and explanations can be found in previously published work (Cooper et al., 2022).

3. Results

3.1 Simulation results

Simulation results for every scenario, summarised in **Table 2**, show marked reductions in $PM_{2.5}$ concentrations when the control framework is implemented with limited use of electricity. It should be noted, however, that in none of the modelled scenarios do mean $PM_{2.5}$ levels fall below the WHO guideline level of 5 μg/m^3 annual mean.

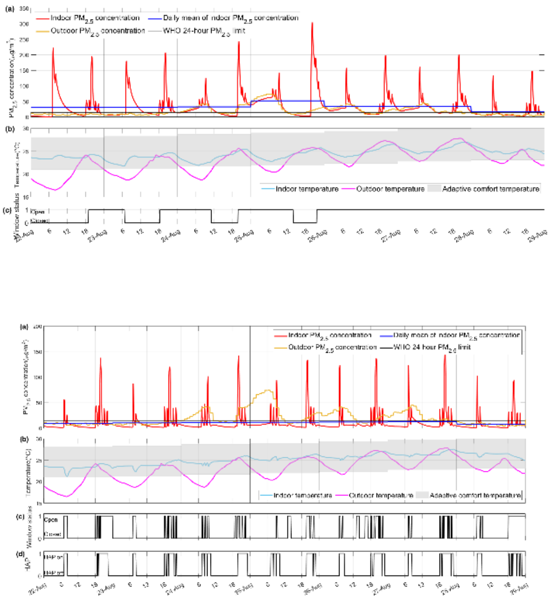
Table 2

Mean $PM_{2.5}$ concentrations in the living rooms of the modelled residence without the use of the control framework (no controls) and with automated control of HAPs and window opening (with controls), along with hours of HAP operation and estimated electricity used by the HAP are included.

	S1		**S2**		**S3**		**S4**	
	No controls	With Controls	No controls	With Controls	No controls	With Controls	No controls	With Controls
Mean $PM_{2.5}$ (μg/m^3)	33.00	10.78	27.03	7.86	36.55	11.37	28.81	8.30
HAP ON duration (hours)	-	38.1	-	33.7	-	34.5	-	30.8
Est. electricity used by HAP (kWh)	-	1.9	-	1.7	-	1.8	-	1.6

Shown in the top of **Figure 1** are the simulation results in which no controls are implemented and there is an active smoker in the home. Peaks in concentration of $PM_{2.5}$ reach levels in excess of 300 µg/m^3 in this case. The bottom of **Figure 1** illustrates the impact of the use of automated controls of windows and HAP. The mean concentration with controls drops from 33 µg/m^3 to 10.8 µg/m^3 with peaks almost halved to less than 150 µg/m^3. Meanwhile, the indoor temprerate was stable within the comfort temperature range.

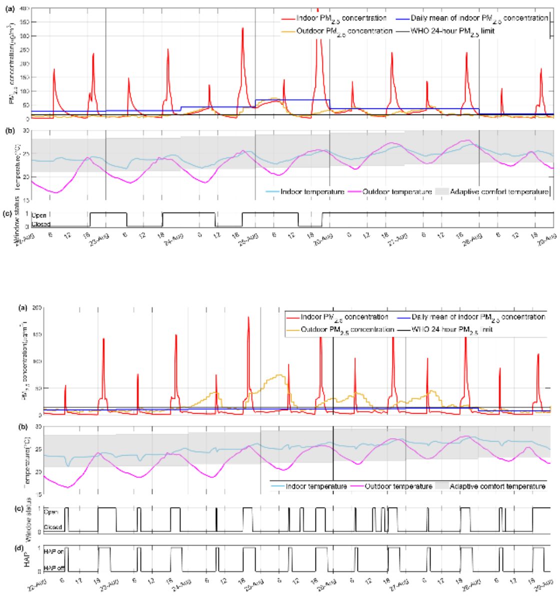
Figure 1 *Scenario 1 without the control framework (above), cigarette smoking indoors, relatively high outdoor $PM_{2.5}$ concentration. Scenario 1 with the control framework (below), cigarette smoking indoors, relatively high outdoor $PM_{2.5}$ concentration.*



Shown in the top of **Figure 2** are the simulation results in which no controls are implemented and there is candle burning in the home. Peaks in concentration of $PM_{2.5}$ exceed 400 µg/m^3 in this case. The bottom of **Figure 2** illustrates the impact of the use of automated controls of windows and HAP. The mean concentration with controls drops from 36.6 µg/m^3 to 11.7 µg/m^3 with peaks of about 150 µg/m^3.Also shown in the bottom of figure 2 is that the indoor temperature stayed inside the comfort temperature range.

Figure 2

Scenario 3 without the control framework, candle burning, relatively high outdoor $PM_{2.5}$ concentration (above) and the same scenario with controls (below).



The results of the other two simulations with lower outdoor air pollution also demonstrated that the implementation of the control strategy could largely reduce both peak and average indoor $PM_{2.5}$ concentration without compromising occupant comfort.

3.2 Health impact assessment

Based on the reduction in the mean concentrations of $PM_{2.5}$ found in the model results, the mean total years of life gained (YLG) per 100,000 people across a lifetime achieved through the use of $PM_{2.5}$-linked controls of window operations and air purifiers is estimated to be nearly 100,000 for each of the modelled scenarios. That is, there is nearly one year of life gained per person in a population using this control strategy.

4. Discussion

The study presented here advances a framework that controls both HAP operations and window openings to reduce indoor $PM_{2.5}$ concentration without compromising occupant thermal comfort. Most prior studies focused on thermal comfort and when any other parameter is considered it is typically only CO_2. This work is intended to advance research on the smart window control system and introduce the joint implementation of HAP control. Moreover, this framework associates the reductions of indoor $PM_{2.5}$ concentrations from adopting control strategies with health impact assessments.. The health impact assessment can be seen as a health benchmarking method to evaluate different control systems.

The current model has now been demonstrated to estimate a range of different occupant behaviours and outdoor conditions. Future work should include the application of the framework and model in different housing types in different climates.

The reliability, and value, of health modelling results is subject to the accuracy of available sources of information, and the ability to add scientific credibility when those sources are uncertain. Results from verified air quality simulations can be used to provide a customisable dataset to add to the predictive power of health modelling when empiric data aren't available. The control framework proposed in this work could be improved with greater integration of the building simulation to modelled health outcomes. Additionally, the life-table model used here does not consider morbidities, such as asthma, which are associated with $PM_{2.5}$.

5. Conclusion

This study aimed to advance the use of a building control framework that integrates home air purifiers and window control systems to reduce indoor $PM_{2.5}$. The framework was tested with new simulation scenarios. The results showed substantial reductions in indoor $PM_{2.5}$ at a low energy cost whilst maintaining thermal comfort. The improvement in indoor air quality is estimated to lead to meaningful health benefits.

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7. Appendices

Figure A1

Scenario 2 without the control framework, cigarette smoking relatively low outdoor $PM_{2.5}$ concentration (above) and the same scenario with controls (below).

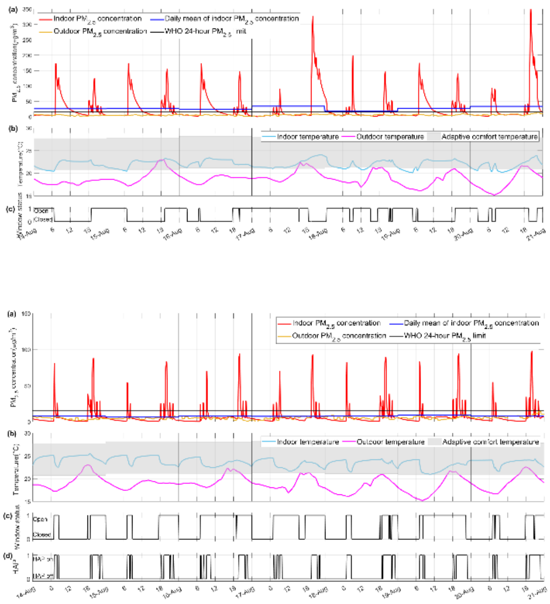
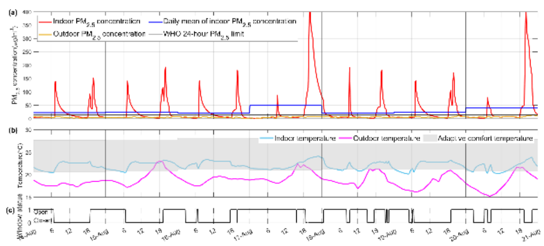
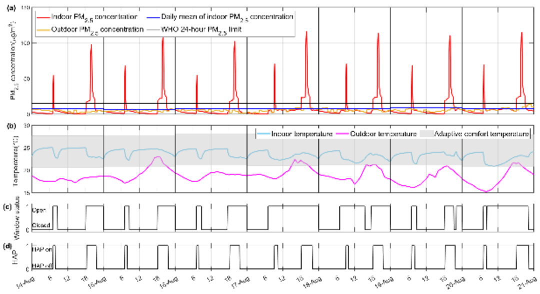


Figure A2

Scenario 4 without the control framework, candle burning, relatively low outdoor $PM_{2.5}$ concentration (above) and the same scenario with controls (below).




(a)
Indoor PM2.5 concentration
Daily mean of indoor PM2.5 concentration
Outdoor PM2.5 concentration
WHO 24-hour PM2.5 limit
PM2.5 concentration (μg/m3)
(b)
Indoor temperature
Outdoor temperature
Adaptive comfort temperature
Temperature (°C)
(c)
Window status
Open
Closed
(d)
HAP
HAP on
HAP off
14-Aug
15-Aug
16-Aug
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug