The use of portable air purifiers for the reduction of $PM_{2.5}$ in residences: Effects on indoor pollutant concentrations, perceived air quality, and mortality

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Statement of Originality

I, Elizabeth Lydia Cooper, confirm that the work presented in this thesis is my own. Where work of others has been used, including information derived from other sources, it is fully acknowledged in the text and in captions to tables and illustrations.

In addition, this thesis does not exceed 100,000 words in length, excluding the appendices. It is confirmed that all references were correct at the time of submission.

Signed

26th September 2021

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In loving memory of my mother,

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Abstract

Background: Time at home accounts for 65% of people's time indoors, on average. It is, therefore, important to understand the quality of air in homes, how occupants perceive it, and how best to improve it to effectively manage the total exposure to airborne pollutants. Exposure to particulate matter, in particular, is associated with negative health outcomes that account for significant morbidity and mortality worldwide. Technologies are rapidly being developed and adopted to mitigate indoor air pollution. Portable home air purifiers (PAPs), especially those that employ HEPA filters, have the potential to effectively clean the surrounding air of harmful pollutants of both indoor and outdoor origin.

Aims: The three primary aims of the research presented here were to 1) test the field performance of commercially available air purifiers in bedrooms, 2) explore the primary drivers of occupants' use of portable air purifiers, and 3) estimate the impact of the use of portable air purifiers on health outcomes associated with $PM_{2.5}$ exposures at home in the UK.

Methods: The work presented here included air quality monitoring at 18 flats in three modern buildings at two sites in London from July through the end of December 2019. At the beginning and end of the monitoring period the participants were asked about several aspects of the environmental quality of their homes, as well as about their wellbeing and sleep whilst at home. Results from the monitoring and interviews were used, along with information from published literature, to parameterise health impact models to evaluate the potential for impact of PAP use on mortality and childhood asthma.

Results: Findings from the present study showed that $PM_{2.5}$ concentrations in bedrooms were reduced by a mean of 45% over 90 minutes with PAP use. Participants' subjective assessment of the indoor air when the PAP was on was positive. The predominant motivation and indicator of PAP use was thermal comfort, therefore if air purifiers are to be used for year-round removal of particulate matter it is important to consider other motivations of air purifier use, and/or other control solutions. The measured changes in indoor $PM_{2.5}$ exposures in bedrooms from the monitored flats utilising PAPs in London were one metric used as a parameter in modelling the potential health impact of several PAP use scenarios across a wider UK population. Estimates of impacts on mortality outcomes (years of life gained and mean days gained) were calculated based upon life table modelling methods. The central scenario showed an increase in the number of years of life (YLG) in the UK of roughly 23 million over the modelled period. This YLG translates to an additional 138 and 120 days of life expectancy for males and females, respectively. Health impacts of reductions to exposure on childhood asthma were also estimated, and the number of QALYs saved by using appropriately sized and well-functioning air purifiers in the bedrooms of children during sleep was estimated to be 1,116 per 10,000 children annually.

Conclusions: In the work presented here, PAPs were effective at reducing $PM_{2.5}$ levels in bedrooms. The associated reductions in exposure of the UK population whilst at home could, according to health impact models, add an average of more than 4 months to life expectancy. However, because occupants' use of the PAPs was shown to be associated with thermal conditions and not $PM_{2.5}$ concentrations, sensor-controlled devices may be necessary to ensure that the devices are operating as intended and to their full capacity.

Further work is needed to verify the modelled connection between home air purifier use and improvements in health, as there is limited evidence found in the literature. Additionally, consideration should be given to the larger societal context in which recommendations for interventions are made. Indoor air quality may be especially poor in areas experiencing the greatest risk of economic deprivation. Therefore, although these devices may provide health benefits to those that have them, a reliance upon expensive devices to mitigate poor indoor air quality could exacerbate existing inequalities.

Impact Statement

This thesis aimed to answer questions about the impact of commercially available portable home air purifiers (PAPs) on the reduction of harmful indoor pollutants; the motivations for PAP use; and the potential health benefits to the UK population from the use of PAPs. These questions are important because people in the UK spend about 65% of their time at home, where pollutant concentrations can be much higher than in outdoor air. One pollutant of particular concern is particulate matter less than 2.5µm in diameter, ($PM_{2.5}$), which is a pollutant that is readily filtered with PAPs equipped with High Efficiency Particulate Air (HEPA) filters. $PM_{2.5}$ contributes to many serious health effects, including lung cancer, stroke, heart disease, and asthma. The impact of the understanding of how to lower indoor $PM_{2.5}$, what motivates people to make changes that reduce those levels, and what the effect of lower $PM_{2.5}$ levels may be on the health of the population would occur on an individual, local, national and international scale.

The first part of the thesis measured the effect of PAPs on $PM_{2.5}$ in the bedrooms of flats in London. The length of the monitoring period (6 months), and the collection of PAP operational data via the cloud, were both novel study approaches, that are likely to impact future work in the field. The findings from this phase of the study will contribute to the knowledge of the effectiveness of PAPs *in-situ* with objective confirmation of the state of the PAP – ON/OFF, fan speed, duration of operation. Manufacturers and designers can use this information to better understand the real-world efficacy of these devices in reducing $PM_{2.5}$. Additionally, this monitoring provides information on patterns of use that could impact the way industry provides operational instruction or control of devices.

The second part of the work aimed to explore users' motivations for PAP operation. The impact to research is substantial, as no previous work was identified that explored the drivers behind the use of PAPs or similar devices. This portion of the thesis work investigated occupants' opinions about their home, and what motivated them to make any changes when they were dissatisfied with its environment. The main finding of this work was that occupants were generally unhappy with the high temperature of their homes in the summer. No significant associations between measured levels of $PM_{2.5}$ and dissatisfaction with air quality were found. This finding has significant impacts for designers, occupants, public health experts and policymakers. Because if occupants do not perceive poor indoor air quality, they may not use the PAPs for their intended purpose and the benefits to health from PAP use will be lost.

The work from this thesis has impacts on the direction of future research and on the development of similar technologies. For example, PAP control options which discourage people from making changes that lead to poorer air quality may be one approach to ensuring that the devices are working as intended and to their full capacity. Another, or additional, option is to provide warning systems that notify occupants when they might want to take some action to improve air quality. Integrated sensors, default ON (user must opt-out of PAP use), and integration with ambient air quality data are also options available to allow PAPs to function more effectively to reduce $PM_{2.5}$ for the greatest impact to public health.

Key Messages

As noted, this work provides several important contributions to the field, for manufacturers of these types of devices, policymakers, designers and occupants. The following are some of the key messages for specific built environment actors.

Policymakers

- Policies that direct or mandate the use of portable air purifiers for the management of $PM_{2.5}$ should include clear guidance on the use of the devices. Specifically, PAPs without modes that respond to measured IAQ should be left 'ON' during occupied times regardless of temperature or time of year.

- Any scheme that includes the use of PAPs in residences must include an educational component for the end-users that explains their function, provides information about IAQ, and introduces concepts of health impacts associated with poor air quality.

Designers and building operators

- Mechanical ventilation which incorporates the use of HEPA filtration is likely to provide the most comprehensive (whole dwelling) reduction in $PM_{2.5}$.

- When mechanical ventilation is not an option, designers or building operators rely upon PAPs to reduce $PM_{2.5}$ indoors these devices should be located in rooms with the highest use (i.e., bedrooms) and highest source load (i.e., kitchens).

- PAPs that include integrated $PM_{2.5}$ sensors and operate in response to high levels of PM should be used whenever possible.

Device manufacturers

- Integrated sensors, default ON (user must opt-out of PAP use), and integration with ambient air quality data would allow PAPs to function more effectively to reduce $PM_{2.5}$ for the greatest impact to public health.

Occupants

- Users of PAPs at home should be informed that they may not be aware of poor indoor air quality in their homes and therefore using PAPs in ‘auto’ mode, if available, will offer the best protection against high levels of $PM_{2.5}$.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

AER	*Air exchange rate*
BUS	*Building Use Studies*
CADR	*Clean Air Delivery Rate*
CAV	*Constant Air Volume*
CHD	*Coronary Heart Disease*
COMEAP	*Committee on the Medical Effects of Air Pollutants*
COPD	*Chronic Obstructive Pulmonary Disease*
DALY	*Disability Adjusted Life Year*
EIT	*European Institute of Technology*
EPC	*Energy Performance Certificates*
GBD	*Global Burden of Disease*
GHG	*Green House Gas*
GP	*General Practitioner*
HEPA	*High Efficiency Particulate Air*
HHSRS	*Housing Health and Safety Rating System*
HIA	*Health Impact Assessment*
HRV	*Heart Rate Variability*
HVAC	*Heating Ventilation and Air Conditioning*
IAQ	*Indoor Air Quality*
IHD	*Ischemic Heart Disease*
LOD	*Limit of Detection*
LRI	*Lower Respiratory Infection*
MERV	*Minimum Efficiency Reporting Value*

MVHR	*Mechanical Ventilation with Heat Recovery*
ONS	*Office of National Statistics*
PAP	*Portable Air Purifier*
PEFR	*Peak Expiratory Flow Rate*
PIR	*Passive Infrared (sensors)*
PM	*Particulate Matter*
PSQI	*Pittsburgh Sleep Quality Index*
QALY	*Quality Adjusted Life Year*
RH	*Relative Humidity*
RR	*Relative Risk*
SBS	*Sick Building Syndrome*
TVOC	*Total Volatile Organic Compounds*
USEPA	*United States Environmental Protection Agency*
VAV	*Variable Air Volume*
WHO	*World Health Organisation*
YLG	*Years of Life Gained*
YLL	*Years of Life Lost*

Chapter 1 Introduction

1.1 Context and relevance of research

The contribution of indoor air pollutants from our time spent at home to total exposure is substantial, as people spend more than 65% of their time there (Klepeis, 2001). It is therefore important to understand ways to reduce exposures and to assess the impact those reductions may have on mortality and quality of life. Indoor air pollution levels, including particulate matter, can, in many locations, exceed health-based standards developed by the World Health Organization for both chronic and acute exposure (Logue et al., 2012). The scale and significance of the contribution of indoor air pollution to total exposure, as well as the negative health impacts associated with exposure, has been demonstrated in past research going back decades (e.g., Pope et al., 2020; Samet, 1993; Weisel et al., 2005).

There are several types of indoor air contaminants, of both outdoor and indoor origin, that may impact human health. These include, nitrogen dioxide (NO_2), volatile organic compounds (VOCs), and particulate matter ranging in size from approximately 10 μm to <0.01 μm. NO_2 is a pollutant that is most often associated with outdoor sources (specifically vehicular traffic), but can originate from unvented indoor combustion. The health effects of NO_2 are primarily pulmonary irritation, but it has been implicated in exacerbations of asthma and increases in respiratory infections. VOCs are used widely in household and building products (such as paints, adhesives and cleaning products), and are often several times higher indoors than out. Health effects are also wide ranging and vary depending upon the specific compounds of exposure, but include eye, nose and throat irritation, headache and even cancer.

The type of air purifiers used in the work of this thesis are designed to be most effective against particulate matter, and particulate matter less than 2.5μm in aerodynamic diameter ($PM_{2.5}$) is of particular concern because it has been shown to impact multiple negative health outcomes including; cardiovascular diseases (Ostro, 1989), asthma (Schwartz, 1993), bronchitis (Anderson et al., 2012), premature mortality (Crouse et al., 2012; Laden et al., 2006; Pope & Dockery, 2006) and lung cancer (Pope, 2002). Indoor sources of $PM_{2.5}$ include cooking, smoking, and burning of candles and incense. The composition of $PM_{2.5}$ in homes varies by location, but is typical described as a mixture of liquids, such as cooking oil vapour, and solids, such as soot.

This thesis focusses on the air quality of residences in the UK, and includes a monitoring study in flats in London. Urban background $PM_{2.5}$ levels have improved in the UK from a recent (2011) high of 13.7 $\mu g/m^3$ to 9.9 $\mu g/m^3$ in 2019 (Defra, 2021). However, levels in some areas remain high, and indoor levels are often much higher than those outdoors due to indoor generation of $PM_{2.5}$. The adoption of technologies to mitigate indoor air pollution is increasingly common, and previous studies have considered the health benefits of different methods of particulate filtration on specific conditions, such as asthma (Batterman et al., 2012; Fisk, 2018; Fisk & Chan, 2017b).

However, impacts on the wellbeing of a healthy adult cohort have been poorly described and past research has failed to address the complex relationships that exist between the indoor environment and people. Most of the research in the built environment examines environmental influences on perception and behaviour in isolation. A multi-domain approach - that is, a method that examines the combined effects of environmental influences on occupant behaviour (Torresin et al., 2018) - is used in this thesis.

Schweiker et al. (2020) reviewed multi-domain approaches investigating indoor environment behaviour and found that studies remain limited despite recognition that the stimuli that influence occupants' behaviours and perception are multi-factorial and varied (e.g., thermal, visual, indoor air quality (IAQ)). This thesis uses a multi-domain approach to 1) examine the impact of commercially available air purifiers used in actual bedrooms in London on indoor $PM_{2.5}$ concentrations, 2) understand occupants' perception of indoor air quality, 3) explore how and why portable air purifiers are used by occupants, and 4) estimate the potential impact of the use of portable air purifiers on population health outcomes associated with $PM_{2.5}$ exposures at home.

The work presented in this thesis considered multiple physical (i.e., IAQ measurements, temperature and relative humidity), contextual (i.e., country and season) and personal (i.e., thermal sensation, IAQ preferences, perception of control over environmental variable) variables to provide a more integrated and holistic analysis of PAP operating behaviour. This method yielded new insights into the understanding of occupants' perceptions of their homes, and behaviours that may impact air quality.

1.1.1 Changing climate, changing buildings

In an effort to mitigate the rate and impact of climate change, the UK has set targets to reduce greenhouse gas (GHG) emissions. Buildings represent a large share of current emissions, accounting for approximately 23% of GHG emissions in the UK (Climate Change Committee, 2020).

The UK has adopted a goal of 'net-zero' CO_2 emissions by 2050, involving economy-wide reductions in emissions of around 90% below 1990 levels, and carbon removal measures to offset the residual emissions. Given the large contribution to emissions from the building sector, and that the building stock is estimated to be comprised primarily of the existing buildings, energy retrofits are likely to be an important means of achieving the energy and GHG emission goals. As a number of studies have highlighted (e.g., Davies & Oreszczyn, 2012; Mavrogianni et al., 2013; Shrubsole, 2014) an unintended consequence of improving levels of airtightness of the domestic housing stock to increase energy efficiency may be inadequate ventilation (Gupta & Kapsali, 2016). Poor ventilation could lead to increased levels of unhealthy indoor-generated air pollutants, which may not be perceived by occupants, and higher risks of exposure.

1.1.2 Improved indoor air through filtration

The most common equipment currently available to remove indoor airborne particles for in-home use are portable air purifiers (PAPs) which utilise High Efficiency Particulate Air (HEPA) filtration as the primary mechanism of air cleaning. These devices have several advantages over other filtration methods, including they are simple to install, can be located where people spend most of their time, can be relocated, and they do not require a central air handling system. Previous research has reported substantial and meaningful reductions in $PM_{2.5}$ in spaces using these devices (McNamara et al., 2017; Shao et al., 2017). However, much of this research has targeted occupants with specific health conditions (e.g., asthma), or specific outdoor events (e.g., wildfires) (Brugge et al., 2017; Maestas et al., 2019; Park et al., 2017; Spilak et al., 2014; Vyas et al., 2016; Weichenthal et al., 2013). Studies of use in the general adult population without specific ambient conditions are uncommon, and none were found that monitored IAQ for longer than 3 weeks (Huang et al., 2020; Kajbafzadeh et al., 2015).

Substantial reductions in $PM_{2.5}$ have been reported from monitoring in spaces using these devices; from a low of 29% in a study in Canada (Barn et al., 2018) to as much as 82.7% in China (Zhan et al., 2018) with many studies reporting reductions of approximately 50% (e.g. McNamara et al., 2017; Shao et al., 2017). Modelling studies have reported similar reductions to those seen in the measured data. In one such study in the USA (Fisk & Chan, 2017b) reductions of $PM_{2.5}$ concentrations were simulated for a number of scenarios, including a 45% reduction using portable air purifiers in homes without forced air systems, a scenario which closely resembles the typical conditions in London flats.

Building ventilation systems, infiltration rates, and location of the air purifier in the building are all well considered and described in the literature as factors that affect air purifier performance (Novoselac & Siegel, 2009; Shaughnessy & Sextro, 2006; Whitby, 1983). However, how, or why people use air purifier devices has not been adequately studied. This information is critical in understanding the primary drivers and barriers behind PAP use which can affect the effectiveness of the devices in reducing $PM_{2.5}$. If PAPs are not operated when IAQ is poor, the potential for health benefits from reduced exposure is compromised. Whilst other occupant behaviours affecting indoor air quality such as window opening behaviour (Yao & Zhao, 2017), and air-conditioning use relative to thermal comfort (Wu et al., 2017), have been well documented, only a couple of studies have looked directly at PAP use and its drivers.

One such study by Pei et al. (Pei et al., 2019) found that in 43 residences in China, that were provided with portable air purifiers, 81.4% did not use the device at all, and of those that used it intermittently (18.6%), the average operating time was between 1-4 hours per day. They concluded that these patterns of use would be insufficient to adequately reduce indoor $PM_{2.5}$ levels. Very different use patterns were reported, although not directly monitored, in a study from the California Air Resources Board (Piazza, 2006). They found that 57% of owners of air purifiers claimed to use them continuously every day. There is little to explain the significant difference between these two studies, other than speculation by Pei et al. that the motivation for the frequent air purifier use reported in California was due to perceived health benefits of their use. It seems unlikely, however, that owners of PAPs in China would be unaware of similar potential health benefits.

1.1.3 Perception of air quality

If occupants are to respond to poor IAQ to reduce the potential of exposure to $PM_{2.5}$ they must be able to know when levels are high. However, the relationship between measured and perceived indoor air quality has not been shown to be strongly linked. A study in France assessed the perception of air quality in homes and found that there was little correlation between occupants' perceived air quality and the measured parameters (including particulate matter) (Langer et al., 2017). In the study, occupants generally described their home more favourably than visitors, who did a better job of assessing air quality. However, visitor perceptions were only strongly correlated with the smoking habits of the occupants and the season in which they visited. Of the possible indoor air pollutants, volatile organic compounds (most which have an odour), including acrolein and acetaldehyde, had the largest impact on the perception of indoor air quality. The perception of air quality has also been shown to be strongly influenced by the thermal conditions and relative humidity of a space (Fang, 2004). Little evidence exists that indicates people readily perceive poor air quality due to $PM_{2.5}$. A study by Rotko et al. (Rotko, 2002) found that, although people expressed annoyance with air pollution, there was little correlation between annoyance and measured $PM_{2.5}$ concentrations. Risk of exposure may be especially high at home where people spend so much of their time, because they do not perceive $PM_{2.5}$ and therefore do not act to mitigate unhealthy levels arising when ventilation is inadequate. Additionally, home is different from most other indoor settings as it is where people sleep, a time when they naturally cannot take action to remedy poor air quality.

1.1.4 Health impact assessment of air pollution interventions

Health impact assessments (HIAs) are commonly used in the study of air pollution to assess the health effects of real and potential exposure reduction strategies, especially when empirical studies are not feasible. HIAs are generally based on estimating morbidity, premature deaths and the number of years of life lost or gained (YLLs or YLGs) (Coyle et al., 2003; Leksell & Rabl, 2001; Reshetin & Kazazyan, 2004) using exposure–response functions derived from cohort studies with long-term follow-up such as the Harvard Six Cities Study (Dockery et al., 1993; Laden et al., 2006).

There is sound epidemiological evidence for the effects of $PM_{2.5}$ on health. It is widely acknowledged that long-term exposure to $PM_{2.5}$ increases mortality risk and reduces life expectancy (Pope et al., 2019; Pope, 2002; Wang et al., 2020). Short-term exposure is positively associated with risk of hospital admission and respiratory diseases, as well as diabetes, and vascular disease (Wei et al., 2019). Changes to $PM_{2.5}$ exposure can come from a variety of causes, both from changes to people's environments, both outdoors and indoors, or from changes in their behaviours, such as smoking cessation. The outcomes from these reductions can also take on many forms, depending on the context, and can include reduced GP and hospital visits, improvements to productivity at work or school, or increased life expectancy. What all these contexts have in common is that the assessment is based on predictions of the difference between the status quo and the new scenario, or intervention. The health impact assessment described in this thesis focusses on predicted changes in mortality, and childhood asthma, due to reductions in $PM_{2.5}$ at home through the use of PAPs.

1.2 Research questions

The work presented here aimed to answer several questions about the use of PAPs in homes.

i. How effective are standard, commercially available, PAPs at removing $PM_{2.5}$ from indoor air in the context of typical occupant use?
ii. Do occupants perceive poor indoor air quality due to $PM_{2.5}$ and does it influence occupant behaviour?
iii. What is the potential impact on mortality and life expectancy of PAP use at home?

1.3 Contributions to knowledge

There are several original and novel contributions to knowledge in this thesis:

i. Evidence of the efficacy of commercially available portable air purifiers with typical occupant use, to reduce $PM_{2.5}$ in the air in the rooms in which they are operating.
ii. Evidence that occupants do not perceive $PM_{2.5}$ in the air of their homes, and that thermal comfort, rather than indoor air quality, is the primary driver of PAP use in homes.

iii. Evidence that the improvement to indoor air quality from PAP use could provide population-level benefits to mortality and life expectancy.

This work includes several novel approaches to providing the evidence listed above including, long-term monitoring of indoor and outdoor environmental and air quality conditions at modern, low-energy UK flats with healthy adults; a novel, multi-domain approach to provide a more fundamental understanding of occupant behaviour in the context of PAPs; and, connecting measured levels of reduction in exposure to indoor $PM_{2.5}$ through the use of PAPs in homes to changes in childhood asthma, life expectancy and mortality in the UK population.

1.4 Thesis structure

Some of the content in the chapters of this thesis is based upon three published papers which can be read independently of one another, listed below in Section 1.5 and provided in full in Appendix A. However, this thesis provides a deeper exploration and analysis of the available literature, a more detailed description of the methods employed, and a much-expanded narrative in the discussion than could be provided in the published works. The structure of this thesis is described here by chapter.

Chapter 1 Introduction: Introduces what is known about; indoor air quality in homes, health impacts associated with $PM_{2.5}$, and air purifiers for domestic use. Research aims and objectives are presented, as well as hypotheses to be tested and the academic outputs of the thesis.

Chapter 2 Literature Review: Presents a summary of the current literature in three primary themes, the efficacy and use of portable air purifiers (PAPs); the perception of air quality; and the impact of the use of PAPs on health outcomes.

Chapters 3 Methods – Air Quality Monitoring: Provides the methodology used in air quality monitoring.

Chapter 4 Results – Air Quality Monitoring: Reports the results from the air quality monitoring study.

Chapter 5 Methods – Surveys and Statistical Analysis: Describes the methods used in the collection of occupant information through the use of surveys and interviews. This chapter also presents the statistical analysis applied to the qualitative data.

Chapter 6 Results - Surveys and Statistical Analysis: Reports the results from the qualitative and statistical analyses.

Chapter 7 Methods – Health Modelling: Provides the methods used in the health impact modelling, including a detailed model description and parameterisation, and the testing of sensitivities and uncertainties within the model.

Chapter 8 Results– Health Modelling: Presents the results from the health impact assessment.

Chapter 9 Discussion: Provides an opportunity to explore in more depth the meaningfulness and implications of the work, and includes discussion of:

- The principal findings;
- The strengths and weaknesses of the study;

- Any meaningful differences between the results of this thesis and other studies;
- The impact of the thesis including possible explanations and implications for designers, building operators and policymakers; and
- Unanswered questions and future research.

Chapter 10 Conclusion and reflections: Concluding summary and statement about the findings, their impact and implications for future work.

1.5 Academic outputs of this thesis

As first author, three peer-reviewed journal articles, a peer-reviewed conference paper, and a technical report were derived from the work undertaken towards this thesis. These are listed below, and copies of the papers are provided in Appendix A.

Additionally, several other journal papers and conference papers and presentations used data and analysis from the work of this thesis. These are also listed below, but are not included in the appendix.

Journal Papers

Cooper, E., Wang, Y., Stamp, S., Burman, E., & Mumovic, D. (2021). Use of portable air purifiers in homes: Operating behaviour, effect on indoor $PM_{2.5}$ and perceived indoor air quality. *Building and Environment, 191*, 107621. doi:https://doi.org/10.1016/j.buildenv.2021.107621

Cooper, E., Wang, Y., Stamp, S., Nijsen, T., de Graaf, P., Hofman, J., Inki, T., Driessen, R., Liebmann, J., Geven, I., Vervoort, K., Panxica La Manna, V., Valster, S., de Wolf, P., Peltonen, S., Burman, E., Salminen, A., van Galen, R., Mumuvic, D. (2021). How do people use portable air purifiers? Evidence from occupant surveys and air quality monitoring in homes in three European cities. *Building Research & Information.* (Under review)

Cooper, E., Milner, J., Wang, Y., Mumovic, D. (2021). Modelling the impact on mortality of using portable air purifiers to reduce $PM_{2.5}$ in UK homes. *Environmental Research*. (Under review)

Conference Papers & presentations

Cooper, E., Wang, Y., Stamp, S., Mumovic, D. (2021). Health benefits of the use of portable air purifiers that reduce exposure to $PM_{2.5}$ in residences: The case of childhood asthma in London. *Proceedings of RoomVent 2020*, Online 15-17 February 2021. (Peer reviewed)

Cooper, E., Wang, Y., Godoy Shimizu, D., Tahmasebi, F. (2020) Towards understanding the impacts of the COVID-19 lockdown on indoor air quality and occupant behaviour: A study in London. *Annex 79 OB-20 Symposium on occupant behaviour research*, Odense, Denmark. 22-25 September 2020.

Contributions to other work (not first author)

Tahmasebi, F., Wang, Y., Cooper, E., Godoy Shimizu, D., Stamp, S., & Mumovic, D. (2021). Window operation behaviour and indoor air quality during lockdown: A monitoring-based simulation-assisted study in London*. Building Services Engineering Research and Technology*. https://doi.org/10.1177/01436244211017786

Zhang, S., Mumovic, D., Stamp, S., Curran, K., & Cooper, E. (2021). What do we know about indoor air quality of nurseries? A review of the literature. *Building Services Engineering Research and Technology*. https://doi.org/10.1177/01436244211009829

Wang, Y., Tahmasebi, F., Cooper, E., Stamp, S., Burman, E., & Mumovic, D. (2020). Capturing the diversity of household window operation behaviour: Lessons from a monitoring campaign in London. *Proceedings of the 5th IBPSA-England Conference, 21-22 September* 2020.

Wang, Y., Tahmasebi, F., Cooper, E., Stamp, S., Chalabi, Z., Burman, E., & Mumovic, D. (2021). An investigation of the influencing factors for occupants' operation of windows in apartments equipped with portable air purifiers. *Building and Environment*, 108260.

Under review or in preparation (at the time of submittal)

Wang, Y., Tahmasebi, F., Cooper, E., Stamp, S., Chalabi, Z., Burman, E., Mumovic, D. "Analysis of occupants' interactions with windows in the UK apartment buildings" *(In preparation)*

Wang, Y., Tahmasebi, F., Cooper, E., Stamp, S., Chalabi, Z., Burman, E., Mumovic, D. "A novel framework for reducing indoor $PM_{2.5}$ on the utilisation of occupant behaviour models and home air purifier." *(In preparation)*

Stamp, S., Burman, E., Cooper, E., Chatzidiakou, L., Wang, Y., Mumovic, D. "Defining dynamic indoor-outdoor ratios in buildings." 2021. *(In preparation)*

Book chapters

Thoua, C., Cooper, E., Stamp, S., Mavrogianni, A., Mumovic, D. Indoor air quality in schools. Chapter in Y. Zhang, P. Hopke, Mandin, C. (eds) *Handbook of Indoor Air Quality*, second edition, Springer.

Zhang, S., Cooper, E., Stamp, S., Curran, K., Mumovic, D. Indoor air quality in nurseries. Chapter in Y. Zhang, P. Hopke, Mandin, C. (eds) *Handbook of Indoor Air Quality*, second edition, Springer.

Technical Reports

QUASIMODO: Report on Pilot Studies. 2019 EIT Digital

Chapter 2 Literature Review

2.1 Outline

The chapter is divided into several section beginning with a description of the methodology used in the literature review. Following the methods are three main sections corresponding to the research aims of the thesis, and a conclusion of the review of the literature. The first of the main sections is a review of the available literature on the effectiveness of PAPs in residences to reduce $PM_{2.5}$ concentrations, as well as any studies that have reported findings on associations between reductions in $PM_{2.5}$ and health outcomes. The next section provides a review of research on people's perception of air quality in relation to measured values of indoor pollutants. The last main section is a review of the literature on the methods, types, and validity of both health impact modelling and economic modelling based on the reduction of $PM_{2.5}$ indoors.

2.2 Methods

2.2.1 Search strategy

A preliminary literature review was conducted in early 2019 at the start of the Quasimodo study (Quality of Indoor Air on Sites Matched with Outdoor Air Quality Datasets to Improve Wellbeing Outcomes) a project supported by EIT Digital that included monitoring of 18 flats in London using PAPs. This preliminary review supported project development and the initial synthesis of research questions relevant to Quasimodo. This initial review was supplemented and consolidated through an extensive search of the literature conducted in February 2021 that used the following electronic databases: Web of Science, Medline, and Scopus. A search strategy was developed incorporating key terms to explore the literature, restricted by language (English), and publication date (2000-2020). A summary of search terms used, both individually and in different combinations, can be found in Table 2-1. Additionally, a recent literature review from Cheek et al. (2021) provided valuable information, and a backward search of cited articles expanded, and validated, the search of the databases.

Table 2-1 Summary of literature search terms.

Conceptual theme	**Sub-theme**	**Search terms**
Effectiveness of air purifiers	$PM_{2.5}$ reduction	air clean*, air purif*, HEPA, air filt*, home*, resid*, hous*, particulate matter, $PM_{2.5}$, reduc*, effec*, efficacy, impact, indoor air quality
	Health impacts	(above terms plus) health, respiratory tract diseas*, cardiovascular diseas*, coronary heart disease, CHD, ischemic heart disease, IHD, lung diseas*, lower respiratory infection, LRI, COPD, stroke, asthma, morbidity, mortality
Perception of air quality	-	percept*, $PM_{2.5}$, particulate matter, indoor air quality, home*, resid*, hous*, human, perceived
Health impact modelling	-	Lifetable, model*, health impact assessment, $PM_{2.5}$, indoor air quality, morbidity, mortality, life expectancy, QALY*, simulat*

2.2.2 Eligibility criteria

Exclusion criteria:

- Studies of air purifier use conducted outside of homes, e.g., hospitals, offices, or schools
- Studies by the same author(s) with repeated results
- Studies with poor design, including small case studies, and uncontrolled or poorly defined interventions.

Although not necessarily a reason for exclusion, air purification technology (i.e., HEPA filtration) was used in some cases to narrow the search, as was the inclusion of adults as the primary subjects of health outcome effects.

2.2.3 Classification and assessment of studies

A standardised data extraction form was created to record all potentially relevant information from the selected papers.

Extracted data from each article included:

- First author
- Year of publication
- Study type (e.g., primary research, meta-analysis)
- Population (age of participants and sample size);
- Outcome measures

2.3 Effectiveness of air purifiers for $PM_{2.5}$ reduction

2.3.1 Review of the factors affecting indoor concentration of pollutants and air purifier performance

The indoor microenvironment plays an important role in the concentration of pollutants and their origins (Allen, 2003). Building characteristics, such as air exchange rates (AER), can dramatically affect the efficacy of particulate removal. When AERs rise, the filter treats a smaller fraction of air; the contribution of outdoor pollutants in the indoor air increases; and pollutants from indoor sources become increasingly diluted (Breen et al., 2014). In addition to AER, nearby traffic intensity, cooking and cleaning behaviours, smoking, the use of candles and incense, as well as mechanical actions (such as walking across carpet), have significant effects on particulate emission and deposition (Hussein et al., 2005).

2.3.2 Findings on the effectiveness of air cleaners in homes

The first of two parts to the review of the literature on the effectiveness of air purifiers, this examines only the impact on $PM_{2.5}$ concentrations without considering any co-effects, such as improved sleep or health. An illustration of the review process can be found in Figure 2-1 below.

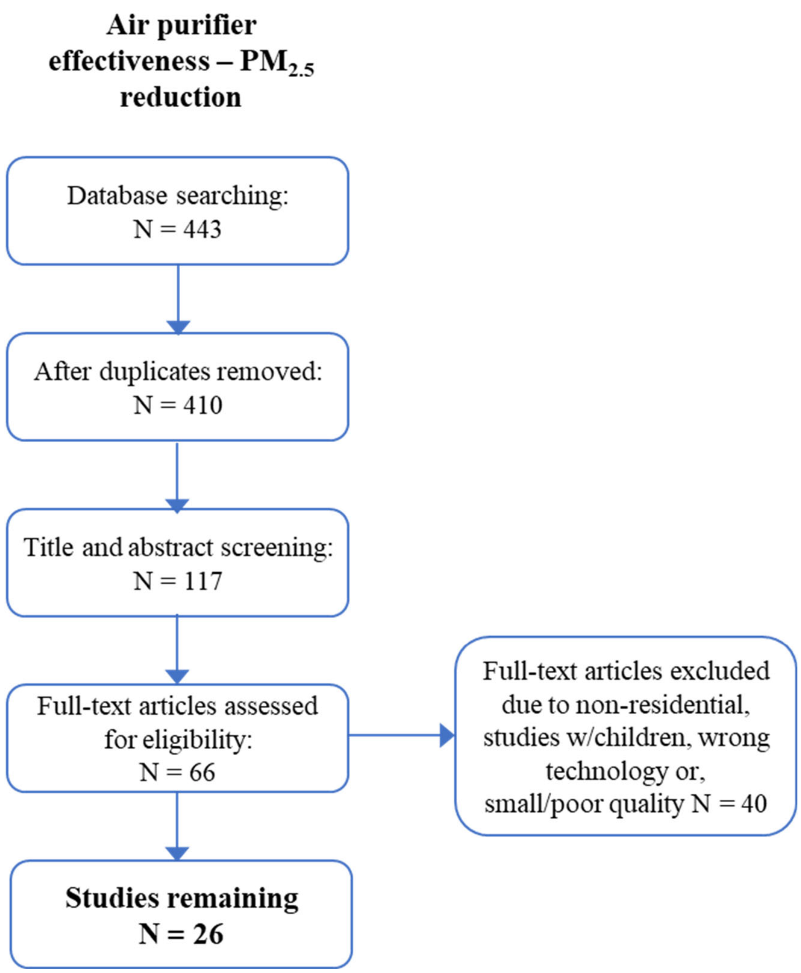

Figure 2-1 Schema of the review process for the effect of air purifiers on $PM_{2.5}$ in residences

The preliminary review investigating air purifier use in homes conducted for the Quasimodo project resulted in the analysis of 17 studies that met the search criteria. Two papers were based on a cohort of pregnant women, the other 15 studies were a randomised crossover design with the PAPs kept in place for the full study duration. In each study, the filtration technology was removed during the control period. The selected studies showed reductions in indoor $PM_{2.5}$ concentrations with the use of air cleaners when compared to the control.

An additional nine studies were added to the initial list of papers on the use of home air purifiers and reductions in $PM_{2.5}$ concentrations in dwellings (Barn et al., 2008; Batterman et al., 2012; Cheng et al., 2016; Hart et al., 2011; Kearney et al., 2014; Maestas et al., 2019; McNamara et al., 2017; Ward et al., 2017; Zhan et al., 2018). All these studies also reported reductions in $PM_{2.5}$ concentrations during the active intervention period compared to the control scenario. In all cases the control involved a placebo or 'sham' air purifier which replicated the intervention but with the filtration device removed.

A report to Health Canada by Wallace (Wallace, 2008) highlighted the importance of the clean air delivery rate (CADR), which is calculated by multiplying the fraction of particles removed in the first pass through the device by the air flow through the filter, as this determines how much clean air is being supplied. The report concludes that air cleaners can reduce particulate levels in homes, but that attention should be paid to the CADR and the efficiency of the filter.

Zhang et al. (2011) conducted a literature review on the use of air cleaning technologies to improve indoor air quality (Zhang et al., 2011). The included studies mainly focused on particulate removal and showed that mechanical filters can efficiently remove particles, suggesting a higher efficiency removal rate for larger particles. A limited number of the studies investigated other pollutant removal (VOCs and O_3) however, the outcomes were inconsistent.

A recent review of the literature summarised the findings of 32 peer-reviewed papers on the change in $PM_{2.5}$ with the use of portable air purifiers (Cheek et al., 2021). Of the papers included in this review 24 of the studies were conducted in homes (not including dormitories, which for the purposes of this review are considered as a separate typology), these were included in the summary below (Table 2-2). In addition to those identified in the Cheek et al. review, two other trials were identified through a separate search and included for a total of 26 studies.

The included studies on the impact of air purifiers on $PM_{2.5}$ in homes came from five countries with varying levels of ambient air pollution, building types, climates, etc. Twelve of the studies were from the USA, five were conducted in China, five in Canada, three in Denmark and one was from Mongolia. Percentage reduction in $PM_{2.5}$ in the homes ranged from 29.0-82.7% between the control period and the intervention with the air purifier. Reductions in $PM_{2.5}$ were reported in all the studies, but it should be noted that most had small sample sizes, and many had short sampling periods.

Table 2-2 Studies included in assessment of impact of air purifiers on $PM_{2.5}$

First author, publication year, country	**Study design, sample size, characteristics**	**Study duration**	**Indoor $PM_{2.5}$ concentration (µg/m^3); mean or median, SD during intervention and control; % reduction**
Allen et al., 2011, Canada	Randomised crossover trial, 25 homes, non-smokers	7 days	Mean ±SD (p-value): control: 11.2 ± 6.1 (<0.01) Intervention: 4.6 ± 2.6 (<0.01) %reduction: 58.9
Barn et al., 2008, Canada	Randomised crossover trial, 32 homes, non-smokers	2 days	Mean ±SD (p-value): control: 6.7 ± 20.7 (<0.01) Intervention: 4.2 ± 7.3 (<0.01) %reduction: 37.3
Barn, 2018, Mongolia	Randomised controlled trial, 512 pregnant adults, non-smokers	7 days	GM (95%CI): control: 24.5 (22.2, 27.0) Intervention: 17.3 (15.8, 18.8) %reduction 29.0
Brauner et al., 2008, Denmark	Randomised crossover trial, 21 homes, non-smokers	2 days	GM (95%CI): control: 12.6 (11.2, 14.1) Intervention: 4.6 (3.5,6) %reduction 63.5
Brehmer et al., 2019, China	Randomised crossover trial, 43 children	14 days	Mean ±SD (p-value): control: 34 ± 17 (<0.01) Intervention: 15 ± 9.6 (<0.01) %reduction: 63.5
Brehmer et al., 2020, China	Randomised crossover trial, 43 children	14 days	Median (IQR), (p-value): Control 30 (19) Intervention: 13 (15) (<0.05) %reduction: 55.9
Butz et al., 2011, USA	Randomised 3-arm controlled trial, 126 children with asthma with smoker	7 days	Mean ±SD (p-value): control: 38.9 ± 25.0 (<0.01) Intervention: 17.9 ± 15.2 (<0.01) %reduction: 54.0
Cheng et al., 2016, USA	Randomised controlled trial, 8 homes, non-smokers	12 weeks	5- min aggregated median/mean (p-value): control: 5.2/6.1 Intervention: 2.6/4.0 (<0.001) %reduction: 37.0
Cox et al., 2018, USA	Randomised controlled crossover trial, 43 homes near major road	4 weeks	Median (p-value): control baseline: 9.6 Control filter: 8.2 Intervention baseline: 7.6 Intervention filter: 3.4, (0.0125) %reduction: 58.5

Eggleston et al., 2005, USA	Randomised controlled trial, 97 children with asthma	72 hours	Median (IQR), (p-value): Control 30 (20-45) Intervention: 24 (10-43) (<0.001) %reduction: 36.8
Huang et al., 2020, USA	Randomised crossover trial, 6 homes, non-smokers	21 days	Mean ±SD (p-value): control: 14.2 ± 20.9 (<0.01) Intervention: 8.5 ± 8.3 (<0.01) %reduction: 41.6
James et al., 2019, USA	Randomised crossover trial, 37 homes near major road	2 days	Median (range), (p-value): Control baseline: 10.4 (0.6-53.2) control filter: 7.8 (<LOD-37.9) intervention baseline: 12.0 (0.3-80.9) intervention filter: 4.5 (1.1-18.0) (<0.0125) %reduction 62.5
Kajbafzadeh et al., Canada	Randomised controlled trial, 44 homes, non-smokers	7 days	Median/mean ±SD: control: 7.5/7.1 ± 6.1 intervention: 3.7/4.3 ± 2.6 %reduction: 40.0
Karottki et al., 2013, Denmark	Randomised controlled trial, 27 homes, non-smokers	14 days	Median (5th-95th percentile): Living room: control: 8 (3.4, 20.7) intervention: 4.3 (0.2, 12.2) Bedroom control: 7.6 (1.4, 19.2) intervention: 3.7 (1, 14) %reduction: Living room:46.3 Bedroom: 51.3
Liu et al., 2018, China	Randomised crossover trial, 20 homes, non-smokers	14 days	Mean ±SD: control: 58.24 ± 52.74 Intervention: 37.99 ± 45.89 %reduction: 34.8
Maestas et al., 2019, USA	Randomised crossover trial, 40 homes, non-smokers	3 days	Mean ±SD, (range) (p-value): control: 17.5 ± 16.9 (4.1-117.5) LE: 8.4 ± 5.4 (1.3-39.5) HE: 7.0 ± 4.5 (1.1-30.8) (<0.001) %reduction: LE: 52.0 HE: 60.0
McNamara et al., 2017, USA	Randomised controlled trial, 48 homes, wood stoves	5 months	Medina (range): control baseline: 19.8 (6.0, 101.9) Control filter: 22.0 (2.4, 163.2) intervention baseline: 15.7 (6.1, 63.1) intervention filter: 5.7 (0.7, 65.6) %reduction: 66.0
Morishita et al., 2018, USA	Randomised crossover trial, 40 homes, non-smokers	3 days	Median/mean ±SD: control: 13.1/17.5 ± 13 LE: 7.8/8.4 ± 3.9 HE: 6.0/7.1 ± 3.5 %reduction: LE: 52.0 HE:60.0
Park et al., 2017, USA	Randomised crossover trial, 16 homes	12 weeks	Mean ± SEM (p-value): Baseline: 7.42 ± 1.42 week 6 intervention: 4.76 ± 0.65 week 12 intervention: 4.28 ± 0.81 (p<0.001) %reduction: 43.0

Rice et al., 2018, USA	Unmasked trial, 82 participants, smoke in home	5 weeks	Median (IQR), (p-value): pre-intervention: 31 (17, 63) post-intervention: 17 (10,35), (<0.001) % reduction: 45.0
Shao et al., 2017, China	Randomised crossover trial. 20 homes, non-smokers	14 days	Mean ± SD (p-value): 10-day average: control: 60 ± 45 intervention: 24 ± 15 (<0.01) %reduction: 10-day average: 60.0
Spilak et al., 2014, Denmark	Randomised crossover trial, 28 homes	14 days	Mean (95% CI): control bedroom: 8.33 (6.72-9.93) control living: 8.32 (6.95-9.69) intervention bedroom: 4.74 (3.53-6.68) intervention living: 4.48 (3.35-6.06) %reduction: 54.5
Ward et al., 2017, USA	Randomised controlled crossover trial, 98 homes with wood stoves	5 months (winter)	Median (range): Control baseline:16.1 (3.9, 508.2) control filter: 16.9 (2.4, 163.2) intervention baseline: 17.1 (6.1, 163.1) intervention filter: 6.5 (0.7, 65.6) %reduction: 68.0
Weichenthal et al., 2013, Canada	Randomised crossover trial. 37 participants	7 days	Median/mean ± SD: Control: 42.5/61.0 ± 64 intervention 22.0/30.0 ± 30 %reduction: 50.8
Wheeler et al., 2014, Canada	Randomised crossover trial, 31 homes	3 days	Gravimetric median (min-max): Control 3.87 (0.37-30.19) intervention: 1.92 (0.35-11.28) %reduction: 52.0
Zhan et al., 2018, China	Randomised crossover trial, 6 participants	4 weeks	Mean: control: 49.0 intervention: 8.47 %reduction: 82.7

The study that reported the largest total reductions in $PM_{2.5}$ (82.7%) was conducted in China with a mean outdoor concentration of 59 μg/m^3 and a mean indoor concentration before intervention of 49 μg/m^3. The lowest level of reduction (29%) was reported in a study in Mongolia of pregnant women (Barn et al., 2018). In this work, the authors found that the air cleaner effectiveness was greater (40% vs. 15%) when first deployed. However, the authors note that there were technical problems with the controls of the air purifiers that could have led to changes in use between monitored periods.

Limitations of many of the studies include short study durations, incomplete or missing information about ventilation practices, including window operation, and no account of indoor activities that could impact $PM_{2.5}$ concentrations (e.g., cooking, cleaning, etc.). Most of the studies also provided little technical information about the PAPs, or how they were deployed or operated. Adherence to study directives (e.g., when the PAP was on, or fan speed) was generally not monitored, or relied only on occupants' reports. Additionally, the location of the PAP (e.g., living room, child's bedroom), and building or room characteristics varied widely between studies.

Most of the reviewed studies found that when sized appropriately for the room and operated continuously PAPs effectively reduce $PM_{2.5}$ indoors. Gaps in the literature on the effectiveness in reducing $PM_{2.5}$ indoors that this thesis aims to fill includes, 1) the effects of using PAPs in modern, well-insulated and airtight, low-energy flats in the UK, 2) monitoring of actual PAP operation (e.g., ON/OFF, fan speed, etc.), 3) long-term measurement of a range of IAQ parameters, and 3) differential contributions of outdoor source and indoor generated $PM_{2.5}$.

2.3.3 Air purifiers and health

The effectiveness of air purifiers to improve health outcomes was treated as a second sub-theme in the literature review, within the broader category of effectiveness of air purifiers, although there was some overlap in the studies identified in the search. The search overview is illustrated in Figure 2-2 below.

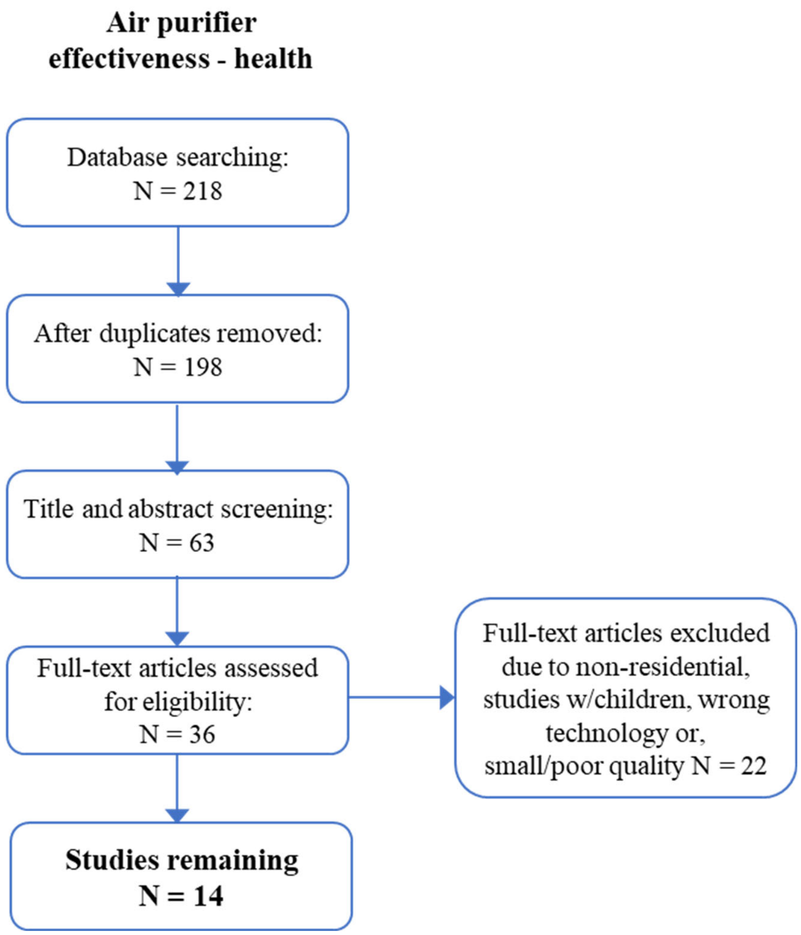

Figure 2-2 Schema of the review process for the effect of air purifiers on health outcomes

Thirteen of the studies measuring air-quality impacts also undertook epidemiological assessments. These are included in Table 2-3 below, along with one additional epidemiological study. These included four reviews, and one systematic review/meta-analysis. The reviews explored a range of different air cleaning technologies with different target pollutants. The review articles, as well as all other papers included in the literature review, are summarised in Table 2-3 below. Six of the papers are from studies done in the USA, another three are from Canada, two are from China, two from Denmark, and one paper is from Mongolia. Most of the studies were randomised controlled or crossover trials.

Table 2-3 Summary of studies on the health impacts of home air purifiers

First author, publication year, country	Study design, sample size, characteristics	Outcome assessed	Risk estimates (percentage change, 95%CI, OR,)	Comments
Allen et al., 2011, Canada	Randomised crossover trial, 25 homes, non-smokers	Reactive hyperaemia index (RHI)	% change (95%CI), between intervention and control group 9.4 (0.9, 18)	Other outcomes assessed, but no significant relationships reported
Barn et al., 2018a, 2018b, Mongolia	Randomised controlled trial, 512 pregnant adults, non-smokers	Pregnancy outcomes - reports of spontaneous abortion and birth weight	Mean difference (95%CI) (Intervention vs control): Preterm birth: 2.37 (1.11, 5.07) Spontaneous abortion: 0.38 (0.18, 0.82)	Other outcomes assessed, but no significant relationships reported
Brauner et al., 2008, Denmark	Randomised crossover trial, 21 homes, non-smokers	Microvascular function (MVF) score	% change (95%CI): 8.1 (0.4, 16.3)	
Butz et al., 2011, USA	Randomised 3-arm controlled trial, 126 children with asthma with smoker	Symptom free days (SFD) in the part 2 weeks	Mean (SD): Control: -0.24 (3.0) Air cleaner group 1.06 (3.4)	Air quality in these smokers' homes did not meet USEPA guidelines even with PAP use
Eggleston et al., 2005, USA	Randomised controlled trial, 97 children with asthma	Symptom free days (SFD) during first 9 months of the study period	Odds ratio (95%CI) p-value: 0.55 (0.31-0.97) .04	Other outcomes assessed, but no significant relationships reported
James et al., 2019, USA	Randomised crossover trial, 43 children with asthma	Health surveys - asthma quality of life (AQLQ)	for "impaired" quality of life at baseline, median score improved 4.93 to 5.47 (p = .021)	Very few statistically significant or clinically meaningful findings

Kajbafzadeh et al., Canada	Randomised controlled trial, 44 homes, non-smokers	Microvascular endothelial function, IL-6 and CRP	Evidence of association between indoor $PM_{2.5}$ and CRP	No statistically significant relationship between $PM_{2.5}$ and endothelial function or IL-6
Karottki et al., 2013, Denmark	Randomised controlled trial, 27 homes, non-smokers	Blood pressure, microvascular and lung function, blood work for inflammation and lung damage markers	No statistically significant effects were recorded	
Liu et al., 2018, China	Randomised crossover trial, 20 homes, non-smokers	Heart rate variability (HRV) and blood pressure	No statistically significant effects were recorded between sham and active filtration	
Morishita et al., 2018, USA	Randomised crossover trial, 40 homes, non-smokers	Primary outcome: blood pressure, secondary outcomes: aortic hemodynamics, pulse-wave velocity, and HRV	Active filtration reduced BP by 3.2 mm Hg (95% CI, -6.1 to -0.2 mm Hg) systolic, 1.5 mm Hg (95% CI, -3.3 to 0.2 mm Hg) diastolic	No improvement was seen in secondary outcomes
Noonan et al., 2017, USA	3-arm randomised controlled trial, 114 children with asthma	Peak expiratory flow (dPFV) and forced expiratory volume (FEV), quality of life surveys	4.1% reduction in dPFV variability (95%CI: -7.8 to -0.4)	Quality of life measures showed no improvement
Park et al., 2017, USA	Randomised crossover trial, 16 homes	Childhood asthma control test (cACT), PFV, nasal symptoms scores	Nasal symptoms scores improved significantly in active group	cACT scores increased in active group, but did not reach statistical significance

Shao et al., 2017, China	Randomised crossover trial. 20 homes, non-smokers	Cardio-pulmonary biomarkers: IL-8, HRV, BP	Reductions in inflammation measured by IL-8 of 58.6% (95%CI: -76.3, -27.6) all participants, -70.0% (95%CI: -83.1, -47.1) COPD patients	No improvements recorded in any other measured outcome
Weichenthal et al., 2013, Canada	Randomised crossover trial. 37 participants	Lung function, blood pressure, and endothelial function	217 ml (95%CI: 23, 410) increase in FEV, -7.9 mm Hg (95%CI: -17, 0.82) SBP, 4.5 mm Hg (95%CI: -11, 2.4) in DBP	High levels of indoor $PM_{2.5}$ due to smoking

Reisman (2002) only considered patients with clinical allergic disease and concluded that there were inadequate data available on the use of air purifiers to prevent and treat allergic disease and therefore they should not be recommended for people with inhalant allergic disease (Reisman, 2001). This review only considered studies until 2000 and allergens, rather than $PM_{2.5}$, were considered as the exposure measurement, which for the purpose of the current work makes this study quite limited in both scope and possible application.

McDonald et al. (2002) conducted a systematic review and meta-analysis on the effect of air filtration systems on asthma across adult and child populations (McDonald et al., 2002). The studies considered in the analysis were from 1976 to 2000 (a timeframe during and since which technologies are likely to have changed and improved), and the intervention considered was the use of a residential air filtration system. Outcomes were signs and symptoms of asthma. The meta-analysis found a small but significant difference in total symptoms and sleep disturbance with domestic air filters and concluded that further randomised trials would be required to determine the effectiveness of air filters for asthmatic patients.

Sublett (2011), considering the effectiveness of air filters and cleaners on patients with allergic respiratory diseases, reviewed studies conducted between 2002 and 2010 (Sublett, 2011). The review considers whole house filtration and portable room and sleep breathing zone air cleaners. A range of study designs was included; modelling or in home, randomised, controlled trials. The studies considered numerous different measures, such as particulate removal, asthma outcomes and personal allergen exposure. The author concluded that the best and most cost-effective approach for populations with allergic respiratory disease was to consider combining whole house filtration with a portable air cleaner or breathing zone filtration.

Fisk (2013) investigated the health benefits of particle filtration in homes and commercial buildings with the main conclusions that particle filtration can have some effect on adverse allergy and asthma outcomes. Delivering filtered air to breathing zones may be more effective in improving health in these subjects, with the largest potential benefits being a reduction in morbidity and mortality from reducing indoor exposure to particles from outdoor origin (Fisk, 2013). The study considers different types of air filtration, various populations and all forms of particulate matter.

Kelly and Fussell (2019) considered a range of microenvironments including the home, schools, offices and transport, and included studies up until April 2018 (Kelly & Fussell, 2019). This review looks at the efficacy of air cleaning technologies at reducing or removing indoor air pollutants and any improvements in indoor air quality, health, and cognitive performance. It explores different air cleaning technologies targeting a range of pollutants and considers all population groups.

Health impacts reported in these studies included those on blood pressure, respiratory parameters, biomarkers, genetics, and pregnancy outcomes. The evidence for such associations was limited and inconsistent, primarily due to small study sizes. However, a substantial body of scientific evidence from previous large-scale cohort studies show positive health impacts of long-term reductions in $PM_{2.5}$ exposure, regardless of where, or how, that reduction is achieved.

Blood pressure is a major risk factor for cardiovascular disease and a systematic review and meta-analysis of 65 epidemiological studies from 2018 found an association with short-term (i.e., a few days) exposure to $PM_{2.5}$ and elevation of blood pressure (Yang et al., 2018). Of the studies included in this review of the impact of air purifiers on health, six considered blood pressure in their analysis (Allen, 2011; Brauner et al., 2008; Karottki, 2013; Morishita et al., 2018; Shao et al., 2017; Weichenthal et al., 2013). Five of these studies did not find a statistically significant relationship between air purifier use and changes in blood pressure. Only Morishita et al. (2018) found a significant association between PAP use and decreases in systolic blood pressure, but found no such relationship to diastolic blood pressure (Morishita et al., 2018). The evidence of a direct effect of air purifiers used in homes on blood pressure, therefore, remains limited.

Cheek et al. (2021) reported that four studies in their systematic review explored the association between air purifier use and heart rate variability (HRV). Low HRV is associated with increased risk of death and cardiovascular disease (Cui et al., 2018; Liu et al., 2018a; Morishita et al., 2018; Shao et al., 2017). Of these, only the study by Liu et al. (2018) found significant diminishment of all HRV parameters in relation to increases of $PM_{2.5}$ concentrations indoors. In general, small, and typically not statistically significant, improvements in HRV among air purifier users were found.

There is some evidence for a positive association between air purifier use and vascular function found in the literature, although studies remain few and limited is size and scope. Allen et al. (2011) reported a significant improvement in endothelial function amount PAP users. Two other studies found an association between reductions in $PM_{2.5}$ levels and improved microvascular function (Brauner et al., 2008; Karottki, 2013).

There is substantial evidence for the effect of $PM_{2.5}$ on respiratory health, but evidence between improvements in lung function and air purifier use in homes remain limited. One study (Weichenthal et al., 2013) found that in homes where occupants were using PAPs lung function was improved in measures of forced expiratory volume in one second (FEV1) and peak expiratory flow rate (PEFR). A study in China found that air purifier use was associated with improvements in airway mechanics (Cui et al., 2018).

In addition to cardiovascular and respiratory outcomes associated with air purifier use, several studies investigated clinical biochemical markers or epigenetic changes. Biomarkers associated with inflammation and oxidative stress are thought to be involved in the route by which $PM_{2.5}$ affects vascular and lung diseases. Four studies included in this review found some level of reduction in markers of inflammation with air purifier use (Allen, 2011; Chen et al., 2018; Chen et al., 2015; Li et al., 2017). The largest effects were seen in China where the highest reductions in indoor $PM_{2.5}$ levels were recorded. Two studies from China found an association between reductions in indoor $PM_{2.5}$ from air purifier use and lower rates of DNA methylation in genes encoding pro-inflammatory and procoagulant proteins (Chen et al., 2016; Liu et al., 2018a). However, due to the limited number of studies, short trial lengths, and small sample sizes, no definitive conclusions can be made on the possible effect of PAPs on epigenetic alterations.

One study focussed on the impact of the use of air purifiers on pregnancy outcomes (Barn et al., 2018). They found that in an area with high levels of pollution (Mongolia), the use of PAPs in homes of pregnant women decreased the risk of spontaneous abortion and increased the number of babies born at full term. Several studies investigated the role of PAP use in childhood asthma and respiratory health (Butz, 2011; Eggleston et al., 2005; James et al., 2019; Noonan et al., 2017; Park et al., 2017). These studies found that the use of air purifiers in the homes of children improved asthma or allergy symptoms.

There are still many unanswered questions with regards to the impact of air purifier use on health outcomes. There are many difficulties in determining effects, even on an epidemiological scale, due to what can be long lags between intervention and outcome, and on the many different environments in which people can be exposed to $PM_{2.5}$ besides their home. Additional challenges include uncertainty in PAP usage, and differences in existing $PM_{2.5}$ concentrations (both ambient levels and those from indoor sources). This thesis cannot answer all of these, and other, questions but does examine, through qualitative methods, occupants' perceptions of wellbeing when using the PAP compared to pre-intervention. This work also differs from most other studies in that it focuses on a healthy adult population, and is not examining effects on specific health conditions. In addition to this, the health impact assessment (discussed in future chapters) will be a useful tool to provide estimated population-level effects of interventions with PAPs in homes.

2.4 Perception of indoor air quality

An initial search for studies investigating the perception of indoor air quality with a focus on homes, particularly related to $PM_{2.5}$, identified 353 publications, 265 papers remained after duplications were removed, and after review of titles and abstracts a further 167 papers were eliminated. Ultimately 98 full texts were evaluated and of these, only 7 met sample size and study design criteria, and included information about occupants' perception of the IAQ in homes, as well as measuring at least one indoor air pollutant other than CO_2 (e.g., NO_2, PM). A schema of the review process is shown in Figure 2-3 and a summary of the included studies can be found in Table 2-4 below.

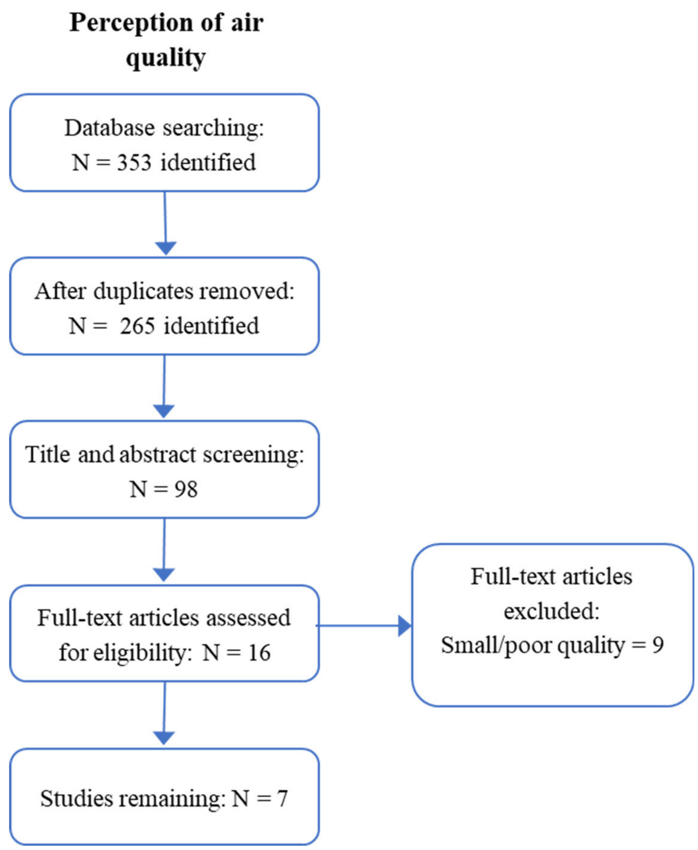

Figure 2-3 Schema of the review process for perception of air quality literature search

Table 2-4 Summary of studies reporting perception of indoor air quality with measured IAQ parameters

First author, publication year, country	**Study design, sample size, characteristics**	**Measured parameters, concentration (if reported)**	**Survey or interview results**
Boso et al., 2020, Chile	81 households, high outdoor $PM_{2.5}$ levels (daily mean 35.4 µg/m^3)	Temperature, RH, $PM_{2.5}$ (daily mean) 33.1µg/m^3 (SD=26.3), PM_{10}	No significant correlation between $PM_{2.5}$ levels and perception of air quality
Földváry et al., 2017, Slovakia	Field study of 114 apartments, in 3 paired buildings half newly renovated	Temperature, RH, CO_2, NO_2, VOCs	Perceived air quality was weakly associated with higher VOCs and lower AER
Hildebrandt et al., 2019, Indonesia	Field study of 27 traditional homes and 14 new apartments	Temperature, RH, TVOCs, formaldehyde, mould risk and multiple chemical sensitivity (MCS)	MCS was positively associated with TVOC levels
Langer et al., 2017, France	567 dwellings	Temperature, RH, CO_2, VOCs, PM_{10} and $PM_{2.5}$	Occupant and inspector perceptions were recorded. IAQ perception was associated with tenure and smoking status
Moreno-Rengal et al., 2018, Mexico	Comparison of a standard-build home and a Passivhaus dwelling	Temperature, RH, CO_2, $PM_{2.5}$	Perception of IAQ not correlated with $PM_{2.5}$. "freshness" of air not significant in perception of overall air quality
Sun et al., 2019, China	32 homes over 4 seasons	Temperature, RH, CO_2, formaldehyde, VOCs, $PM_{2.5}$, O_3	No association between measured $PM_{2.5}$ concentrations and SBS. TVOCs associated with more SBS symptoms
Wang et al., 2018, China	8 'passive' apartments, 8 'conventional' apartments	Temperature, RH, CO_2, $PM_{2.5}$, $PM_{2.5}$	84,4% of residents reported very good, good or general (acceptable) indoor air quality. $PM_{2.5}$ levels were a mean of 92µg/m^3. No association between measured PM and perceived air quality

As is evidenced by the paucity of available literature on the topic, the relationship between subjective perceptions of air quality and objective air pollution exposure remains unclear, and additional research into the associations is needed. A review by Schweiker et al. (2020) of multi-domain approaches into environmental perception and behaviour, identified 18 papers that reported effects of broader environmental factors (i.e. visual, acoustic, thermal, or contextual) on air quality perception, and vice versa. Of these four reported that air was perceived as being of worse quality at higher temperatures (Chatzidiakou et al., 2015; Mølhave et al., 1993; Toftum et al., 2018; Witterseh et al., 2004), but none of these studies were carried out in homes. Although, theoretically, there should not be differences in the way in which people perceive air quality in homes compared to other environments, there is enough evidence to suggest that there is a strong "halo" effect which could affect occupants' opinions of their homes (Boso et al., 2020). The halo effect has been explained by the theory of "bounded rationality", which suggests that people have limits in their ability to perceive risk, or make good choices, even when adequate information is available to them.

Although not explicitly, Langer et al. (2017) explored the halo effect in French dwellings (Langer et al., 2017). Their study measured a number of different environmental parameters including temperature, RH, CO_2, VOCs, and PM_{10} and $PM_{2.5}$ in 567 French dwellings, conducted surveys via questionnaire, and had inspectors assess the homes. The most meaningful relationship between perceived indoor air quality and measured concentrations were made by the outside observers, and the longer the tenure in the dwelling the more positively the occupant perceived the quality of the air in their home, irrespective of the measured values.

The available studies done in homes on occupants' perception of indoor air quality, suggest that people are very poor assessors of actual air quality, and that occupant tenure, temperature, and RH play larger roles in perception than pollutant concentrations.

This thesis aims to close gaps in the understanding of the relationship between measured IAQ variables, with a focus on $PM_{2.5}$, and occupants' perception of the quality of the air in their homes. Knowing how (and whether) people perceive $PM_{2.5}$ is important in understanding how it might influence the use of PAPs. Semi-structured interviews, and surveys, are paired with robust air quality monitoring, as well as the monitoring of other physical parameters, such as RH and temperature, that are known to have an effect on people's perception of air quality.

2.5 Health modelling of reduction in $PM_{2.5}$

No studies were found that explicitly model the health, or economic, impacts of the use of air purifiers in homes. Therefore, in an effort to capture more of the potentially relevant literature, other types of building filtration methods or ventilation improvements were included in this analysis, as were any studies that modelled the effects in buildings other than homes. A search of the literature initially found 77 studies that included the search terms, but after evaluation of the papers (see Figure 2-4 for search schema) only ten studies met all the criteria for inclusion in the review. A summary of these studies can be found in Table 2-5.

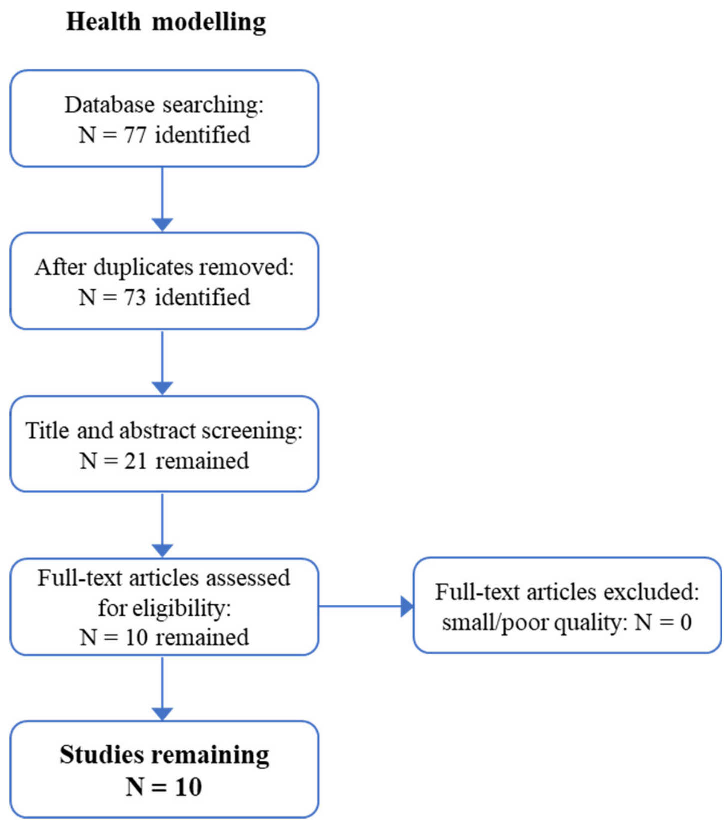

Figure 2-4 Schema of the review process for health modelling literature search.

Table 2-5 Summary of health impact and economic studies of improved IAQ

First author, publication year, country	Study design, sample size, characteristics	Predicted health outcomes and/or economic benefits	Comments
Aldred et al. 2016, USA	Mass balance modelling of activated charcoal filters to reduce ozone in homes, DALYs calculated per USEPA 2012	cost to benefit ratio >1 in 10 of 12 cities modelled	Ozone reductions of 4 to 20%
Bai et al. 2019, China	Monitoring of indoor and outdoor $PM_{2.5}$ at a university in China (university students), DALYs calculated and health impacts assessed by USEtox	Total loss of DALYs per year 1833 from $PM_{2.5}$, including 109 premature deaths	Winter $PM_{2.5}$ mean (indoor) = 41.59 µg/m3, summer mean (indoor) = 11.15 µg/m3
Beko et al. 2008, Denmark	PM10 exposure in an office building with filtration (65, 80 and 95% reductions modelled) cost-benefit model	Financial benefits of filtration far outweigh costs	Work productivity loss was expected due to obtrusive odours from dirty filters
Ben-David & Waring 2018, USA	Office building simulations with different mechanical systems and different filtration efficiencies (MERV 8-16 and HEPA) Predictive cost function accounting for energy use and exposure to Ozone and $PM_{2.5}$	At lower filter efficiencies (MERV 8-11) cost associated with IAQ was ~3 times greater than energy cost	Found that high efficiency filter can mitigate negative effects of ventilation, and higher ventilation rates can increase the efficacy of filtration
Fisk and Chan 2017, USA	Modelling effect of filtration (6 different intervention scenarios) on $PM_{2.5}$ during wildfires	Interventions projected to prevent 11 to 63% of hospital admissions and 7 to 39% of attributable deaths (30% for portable air purifiers alone) during wildfires	Targeted interventions focussed on older people (≥65) were most cost effective (if used for wildfire particle reduction)
Hamilton et al. 2015, UK	Modelled 3 energy retrofit models of English housing stock, with increased ventilation (no filtration) for effect on $PM_{2.5}$, Radon and mould	Positive effects on net mortality and morbidity of 2,241 QALYs per 10,000 persons over 50 years follow-up	Reduction from pre-intervention indoor $PM_{2.5}$ concentration of 9.4µg/m3 to 4.6 µg/m3

Hanninen et al. 2005, Finland	2 modelled scenarios (using a microenvironment approach and probabilistic exposure model), one baseline representative of current standards and one alternative which reduced $PM_{2.5}$ by 27%	Estimated reduction of annual deaths associated with $PM_{2.5}$ in Europe was 27,000-100,000	Potential limitations in applicability to places outside of Europe and in northern climates more specifically.
Milner et al. 2015, UK	Multistate life-table model to assess reductions in indoor $PM_{2.5}$ of 3 µg/m3 in homes in UK	Overall impact increase life expectancy of 2-3 months and approx. 13 million QALYs	Multi-state model with disease recovery
Yuan et al. 2018, China	Health and economic benefits of different ventilation strategies for reducing indoor $PM_{2.5}$ exposure were modelled using a representative urban residence in Beijing	economic savings of 200-800 yuan/person (£22-88/person)	outcomes dependent upon outdoor $PM_{2.5}$ levels and indoor generation - all levels tend to be higher than WHO guidelines
Zuraimi and Tan 2015, Canada	combined mass balanced model, a time-weighted activity exposure model, epidemiological based concentration-response, and monetary valuation method	US$534/year savings in health care by retrofitting residential buildings to comply with min. buildings standards and MERV 15 filters	Other scenarios also modelled with maximum benefit of US$2.3 billion to $3.8 billion/year of health savings.

2.5.1 Health impact assessment

In a study by Bai et al. (2019) the health impacts of both indoor and outdoor $PM_{2.5}$ on university students in the northeast of China were considered. The authors reported that among 145,200 students in this area, there were 109–134 premature deaths due to exposure to $PM_{2.5}$, of which 71–75 were attributed to indoor pollution. Although the study did not include specific interventions to reduce indoor $PM_{2.5}$ the authors noted in their conclusions that the use of air purifiers in dormitories was found to reduce $PM_{2.5}$ concentrations by 57% (Chen et al., 2015), and that this may be an appropriate measure to take in areas of high pollution.

In a modelling study on the impact of air purifiers to reduce exposure to $PM_{2.5}$ during wildfires the authors estimated that in the interventions that utilised portable air purifiers, 30-39% of premature deaths were prevented during each wildfire season in all homes affected (Fisk & Chan, 2017b). Additionally, hospital admissions during the wildfire season were reduced from 48-63%. If only residents aged 65 and older were included in the analyses, 49-65% of excess deaths and 78-100% of increased hospital admissions could be avoided with the use of air purifiers. The authors noted that a targeted approach for interventions to elderly residents would be the most cost effective.

Hanninen (2005) modelled a scenario where exposure to ambient $PM_{2.5}$ levels was reduced by 27% indoors through filtration, although the type of filtration, specific ventilation systems, etc., were not specifically defined in their model. Additionally, their model did not include reductions to indoor sources and the ambient levels in Helsinki, where the study was located, are relatively low (mean concentration 9.8 $\mu g/m^3$). However, despite relatively good air quality and relatively small net improvements in indoor air, the change equated to an estimated 27,000-100,000 deaths prevented each year in Europe if similar reductions were extrapolated to the larger population.

Research by (Milner et al., 2015) used multi-state life-table models to estimate the health effects of housing interventions for energy efficiency. When improvements in ventilation were included in the building upgrades, the average reduction in the $PM_{2.5}$ concentration was 3 $\mu g/m^3$. The improvement in IAQ was shown to provide substantial benefits for mortality and morbidity from asthma, coronary heart disease and lung cancer. The average increase in life expectancy was estimated to be two to three months, with approximately 13 million QALYs gained over the 90-year follow-up period.

Despite other research that investigated PAP effectiveness to reduce $PM_{2.5}$, and known $PM_{2.5}$-related mortalities, this work is the first to use lifetable models to estimate the potential impacts on mortality and life expectancy from reductions in $PM_{2.5}$ at home through the use of PAPs. This information adds to the body of research on the health impacts of other methods of reducing exposure to particulate matter.

2.5.2 Cost-benefit modelling

There is a body of work that begins to address the economic impacts of interventions in the built environment that reduce $PM_{2.5}$ indoors, and this section introduces some of the findings from this work.

Bekö et al. (2008) assessed the impacts of particle filtration in an office building, and found the benefits to health and productivity far outweighed the costs. They modelled a standard office building with F7/EU7 filters changed annually. These filters are much less effective than HEPA filters, only filtering $PM_{2.5}$ at an efficiency of approximately 65%. However, even at this level the health benefits were significant.

In work by Fisk and Chan (2017b) a special condition was modelled, that of air quality during wildfires, and used mass-balance models to estimate concentrations of $PM_{2.5}$ and associated health effects, including cardiac and respiratory events, and deaths. The modelling included the use of different interventions to reduce exposure to $PM_{2.5}$. They found that the economic benefits of the reduction of particulate matter far exceed the costs.

Additionally, Fisk (2013) reported on several studies which used mass balance models to estimate reductions in $PM_{2.5}$, and the associated costs and benefits (Fisk, 2013; Hanninen, 2005; Macintosh et al., 2010; Zuraimi, 2007). All the reviewed papers reported benefits exceeding the costs associated with reductions in PM. Analyses were done in both residential and office buildings in sites in Singapore, Europe, and the U.S.

Research by Aldred et al. (2016) found that activated carbon filters in homes reduced ozone levels between 4 and 20% and that, in cities with large seasonal variations in ozone levels, and the highest removal efficiency the benefit-cost ratio was greater than 1.0. The study authors also reported that for cities with lower ambient ozone levels, for lower efficiencies of ozone removal, and for homes operating HVAC fans less often, costs outweighed the benefits. It should be noted, however, that ozone is a much different case than $PM_{2.5}$ in terms of attributable health outcomes, and therefore the direct applicability of this study is limited.

Ben-David and Waring (2018) reported the effects of filtration on both $PM_{2.5}$ and ozone in offices and the cost function in relation to energy use and exposure. The offices were simulated across multiple climate locations, with both constant air volume

(CAV) and variable air volume (VAV) mechanical systems, different ventilation rates, and different levels of filtration. Costs of filter purchase and regular replacement, along with the additional energy use to overcome the pressure drop, were calculated at approximately 2.5 to 28 US$/occupant/year (for non-HEPA filters). Whereas the estimated value of the health benefits from improved IAQ was greater than 100 US$/occupant/year.

In a study in China, Yuan et al. (2018) reported on interventions to residential ventilation systems to reduce exposure to $PM_{2.5}$ from both outdoor and indoor origin. The results of this study found that benefits of increased air tightness and mechanical ventilation with filtration were most significant when indoor sources of $PM_{2.5}$ exist, in these cases the economic benefits range from 200 yuan/person to 800 yuan/person (~£22-88/person). They noted, however, that filtration efficiencies had to be greater than 90% for these levels of benefits to be manifest.

Based on previous studies that included economic assessments, it is anticipated that a detailed economic analysis of the results from this thesis would suggest savings from the health benefits of reduced exposures to $PM_{2.5}$ would far exceed the costs from equipment, maintenance, and operation of PAPs. However, due to the uncertainties and limitations of cost-benefit analyses, such criteria might not be the most appropriate way to make policy decision on interventions with PAPs. For this reason, the focus of this thesis does not include cost-benefit analyses, nor other measures that assign value (or quality) to life or disability, but rather the focus is on the impacts to life expectancy and mortality. Economic analysis of the effects from reductions in $PM_{2.5}$ similar to those that were found in this thesis can be found in other reports and publications including one from the USEPA (2011) which examined findings on the impacts of the Clean Air Act. including, Readers are encouraged to refer to this, and other documents, and economic analyses will be considered in future work. The results from the thesis will be useful in filling the gap in knowledge on PAP effects at a national scale in the parameterisation of health models that could inform policy, and contribute to the estimations of costs to individuals and government bodies.

2.6 Conclusions of literature review

Despite the substantial work that has been published on the effectiveness of PAPs, and their potential effect on health, there remain many gaps in the literature that this thesis aims to fill. Much of the work that estimated the effectiveness of PAPs was done through modelling only, and those studies that employed monitoring were short (less than one month, and often only a few days), and were typically targeted at specific populations, such as children or adults with health conditions. Additionally, monitoring of the devices was rare, and the use and operation relied upon user reporting.

Rarely were outdoor sensors, that measured the same environmental parameters as the indoor sensors, located at the same location as the indoor monitoring. Given that pollutant composition and concentrations can vary widely depending upon local site conditions, the co-location of indoor and outdoor sensors is an important feature of the methods of this thesis.

The influence of occupant behaviour, window operations, presence of extractor fans and other building characteristics are also often missing from other studies on the effectiveness of PAPs in homes. An additional gap in much of the published work on PAP use are extensive qualitative analyses of occupant satisfaction with the conditions of their homes. This information is critical in understanding potential motivations for PAP use.

Perhaps one of the most novel aspects of this thesis is integration of the results from the semi-structured interviews, monitoring data from the studied flats, data from existing literature with lifetable health models to estimate population effects of PAP use on mortality and life expectancy. The following list summarises additional findings and potential gaps from the literature review.

1. The current evidence demonstrates that the use of air purifiers indoors results in short-term reductions in $PM_{2.5}$, which have the potential to offer health benefits.
2. The observed reductions in $PM_{2.5}$ are anticipated to reduce individual exposure, which is demonstrated to decrease the risk of adverse health effects. However, further research into the effectiveness of air purifiers in relation to improving health outcomes is warranted.
3. In places where source control is not possible (e.g., places affected by wildfires), portable air purifiers are a reasonable, potentially cost-effective, approach to reducing exposures to $PM_{2.5}$ indoors. This may be especially beneficial for vulnerable populations such as the elderly, or those with pre-existing medical conditions such as COPD.
4. Most health outcome studies focus on children or adults with respiratory conditions such as asthma, very few investigate healthy (not pregnant) adult populations, and results on health impacts remain inconsistent and limited.
5. Window operations monitoring is not included in any of the studies.

6. Monitoring of PAP use is often not included. The use of questionnaires or diaries to self-report use may fail to accurately capture the specific time and operation (e.g., ON/OFF, fan speed) of the PAPs.
7. Monitoring, and any interventions, tend to be short-term (e.g., 1-2 weeks).
8. Health modelling at a national scale has not been done for PAP use in residences, and questions about population-based effects therefore are unanswered.

Chapter 3 Methods – Air quality monitoring

3.1 Outline

The chapter begins with an overview of the design and motivation for the study, and then describes the site context. Following the description of the site and its context, the monitoring techniques with specific reference to environmental (physical and air quality), occupancy, and window operation sensors are explained. Finally, the PAPs, their control settings, and their internal monitoring capabilities are described.

3.2 Overview of the design and motivation for the study

Measured data used in this thesis were collected as part of the Quasimodo project funded by EIT Digital. The aim of that research was a proof of concept for a mobile phone application for personalised early warning system (EWS) to enable self-management by the occupant when indoor air quality deteriorates, and to explore the impact of commercially available home air purifiers and EWS on perceived indoor air quality and self-reported wellbeing of occupants. That research also aimed to advance our understanding of time-activity patterns for use in modelling protocols that include prediction of human exposure to pollution from indoor sources. The study was a pilot utilising a convenience sample of 20 households in each of three cities: Eindhoven, The Netherlands; Helsinki, Finland; and London, United Kingdom. The work presented here used only data from the London portion of the study due to the length of the monitoring period (July through December), and the monitoring of a range of indoor environmental parameters, window operations and occupancy which allowed for a more complete analysis of the influencing factors in the use of PAPs. However, the larger study is briefly described here for background.

All participating households were provided with portable air purifiers (PAPs) for use in a bedroom during the study period. In addition to a demonstration of the use of the device by the interviewer, each participant was left with instructions on how to operate the PAP (e.g., power ON/OFF, change fan speed), and the process for reporting any problems or concerns. Additional instructions were provided for completing any online surveys, and participants were given an opportunity to ask questions about the air purifiers and the research, including the motivations for the study.

Indoor air quality monitors were installed in the living room in London, the bedroom with the PAP in Helsinki, and in either the living room or bedroom in Eindhoven. In addition to the separate IAQ monitors, each PAP included an internal 'on-board' $PM_{2.5}$ sensor that sent data to the manufacturer. Outdoor $PM_{2.5}$ levels were monitored at sites close to each building, and window operation was monitored with magnetic sensors in London. Semi-structured interviews were completed at the beginning and end of the study with one adult member of each participating household. Participants were asked about their opinions on the IAQ at their home, their general health, wellbeing and sleep, as well as the motivations for participating in the research. A full description of the study methods and results can be found in the paper, "Why do people use portable air purifiers? Evidence from occupant surveys and air quality monitoring in homes in three European cities" in Appendix A.

3.3 Site Context

This section, and following sections, focus on the context of the London site only. Conventionally, ventilation in UK residences has been through operable openings (i.e., windows and doors) as well as infiltration, and uncontrolled ventilation has been common. Building standards have changed to meet requirements for energy efficiency which has lowered infiltration rates, making intentional ventilation paramount to keeping indoor air quality good (Shrubsole, 2014). Although there are several ways to achieve the required air exchange rates (in the UK for dwellings the rates range from 13 l/s for 1 bedroom to 29 l/s for 5 bedrooms (HM Government, 2010)). These methods of ventilation include, continuous mechanical extract, or supply and extract with heat recovery, however, background ventilators remain a common approach in domestic buildings. Background ventilators (e.g., trickle-ventilators), as with uncontrolled ventilation, do not provide any filtration capacity, leaving the indoor air quality dependent upon the quality of the outdoor air. Additionally, for events of high indoor pollutant generation (e.g., cooking), ventilation rates may be inadequate.

The monitoring in this study utilised a convenience sample of 20 households which, after dropouts, resulted in a sample of 18 flats. Flats were monitored for six months, from July until the end of December, to monitor conditions across three seasons. This timeframe allowed for observations into occupant behaviour and IAQ related to window operations, air purifiers, and heating systems.

Figure 3-1 Images of London site A (left) and site B (right) from Google maps

The 18 residences were located within three buildings at two sites (Site A and B) in Tower Hamlets in east London (see Figure 3-1 and Table 3-1). Both buildings at Site A were completed in 2015, and rely primarily upon natural ventilation and trickle-ventilators in the non-heating months. These flats also have mechanical ventilation with heat recovery (MVHR) that is available during the heating season, and can be used in a by-pass mode for use in non-heating times. The MVHR units are decentralised, one unit per flat, with fan efficiencies between 75-77%, and heat exchanger performance compliance of 92-93%. Filtration with the MVHR is minimal (ISO Coarse 45%), and filter replacement and maintenance (which is the responsibility of the flat occupants) was intermittent, at best. None of the flats had any air conditioning systems. Previous work at Site A included a pressure test which found an air permeability of 2-3 $m^3/(h.m^2)$ at 50Pa. The flats at Site B relied upon natural ventilation and trickle-vents only. Given the age and building characteristics of the building at Site B, the infiltration rate is estimated to also be less than 5 $m^3/(h.m^2)$ at 50Pa. The bedrooms where the PAPs were located (at both sites), ranged in size from approximately $10.5m^2$ to $12.5m^2$ with a ceiling height of 2.5m, and typically had one operable window with an area of approximately $1.6m^2$. Information on the demographics and household activities for all participants can be found in Table 3-2 and graphically in Figure 3-2 below. Each household was asked to locate the portable air purifiers (PAP) in the main bedroom.

Table 3-1 Characteristics of monitored apartment buildings

	Site A	**Site B**
Year built	2015	2006
Stories	13	15
# Units	98	90
Total area (m^2)	7,969	5,938
External wall	U-value: 0.18 ($W \cdot m^{-2} \cdot k^{-1}$) Air mass flow rate for cracks: 0.0011 ($kg \cdot s^{-1}$)	(unknown)
Window	U-value: 0.92 ($W \cdot m^{-2} \cdot k^{-1}$)	(unknown)
Ventilation	Natural + MVHR	Natural ventilation
EPC rating	B	B

Table 3-2 Demographics and relevant activities of participating households

Demographic	Value	Frequency	%
Gender (of lead participant)	Male	10	55.6
	Female	8	44.4
Age (of lead participant)	Under 30	3	16.7
	Over 30	15	83.3
Years at residence	<1 years	0	0.0
	>1 years	18	100.0
Household size	1	4	22.2
	2 to 4	8	44.4
	>4	6	33.3
Children (<18) in household	0	10	55.6
	1 to 2	3	16.7
	>2	5	27.8
Smoking status	Yes	6	33.3
	No	12	66.7
Cooking (per week)	1	0	0.0
	2 to 5	6	33.3
	>5	12	66.7
Cleaning (per week)	1	4	22.2
	2 to 5	9	50.0
	>5	5	27.8
Air freshener use (per week)	never	2	11.1
	1	6	33.3
	2 to 5	1	5.6
	>5	9	50.0
Candle use (per week)	never	4	22.2
	1	11	61.1
	2 to 5	1	5.6
	>5	2	11.1
Pets in home	(Pets were not allowed in these buildings)		
Wood/pellet stove	(Wood/pellet stoves were not available in these buildings)		

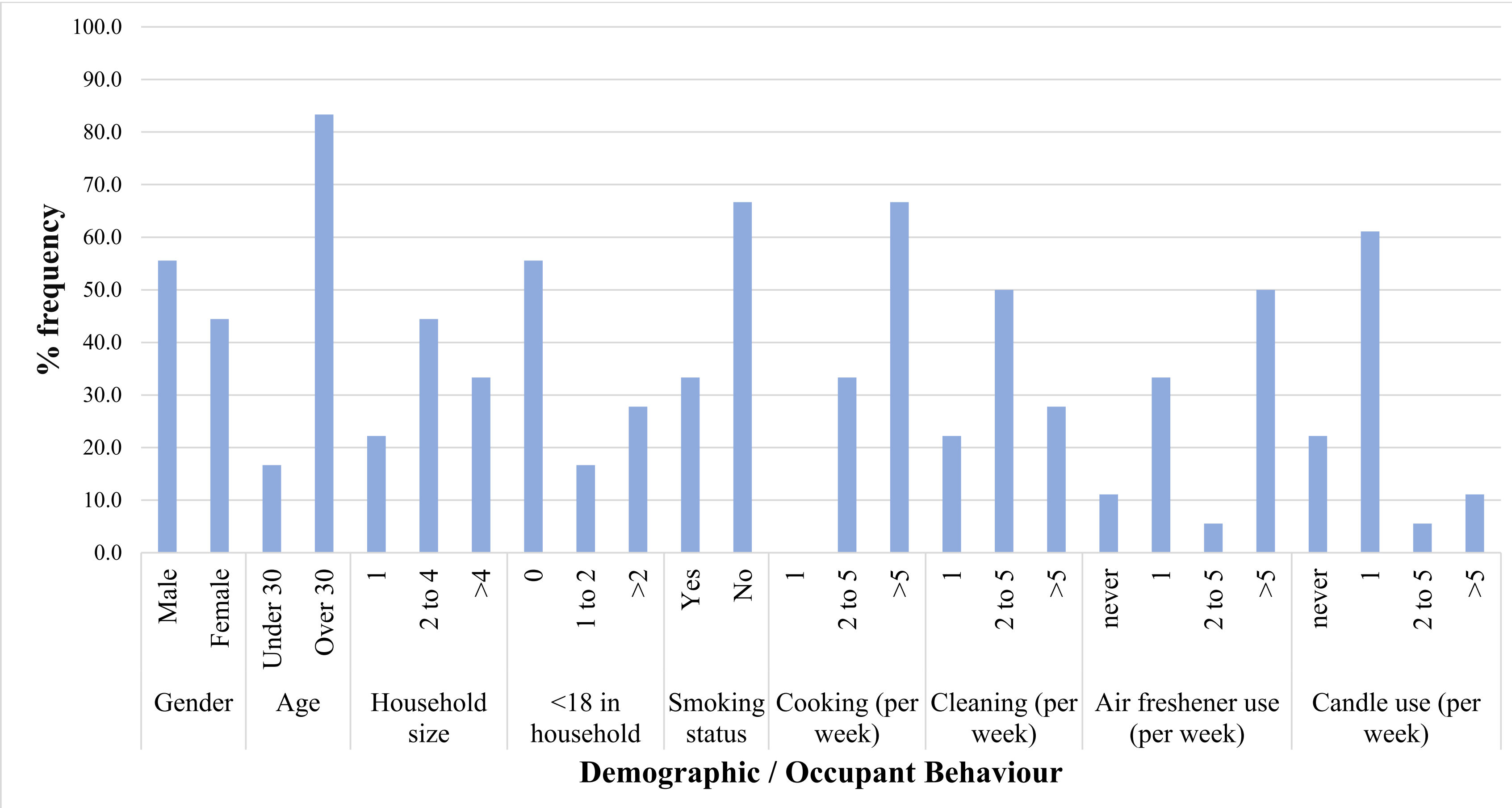

Figure 3-2 Demographics and occupant behaviours reported by study participants

3.4 Monitoring of physical parameters

3.4.1 Indoor environmental monitoring

Eleven flats from Site A and seven flats from Site B were monitored from early July 2019 until the end of December 2019. Overall, 18 living rooms, 17 bedrooms, and 60 opening areas (18 balcony doors and 42 windows) were monitored by sensors which worked in a clustered sensor network.

Table 3-3 Summary of characteristics of monitored flats

Flat index	Site (Year constructed)	Floor level	No. of bedrooms	Floor area (m^2)	No. of occupants	Study period
Flat 1	A (2015)	ground - 3rd	4	127	5	08/07/2019 – 27/12/2019
Flat 2	A (2015)	9th - 13th	3	100	4	08/07/2019 – 27/12/2019
Flat 3	A (2015)	4th - 8th	3	100	4	09/07/2019 – 27/12/2019
Flat 4	A (2015)	9th - 13th	3	100	5	11/07/2019 – 27/12/2019
Flat 5	A (2015)	9th - 13th	1	50	2	13/07/2019 – 27/12/2019
Flat 6	A (2015)	9th - 13th	2	70	1	19/07/2019 – 08/01/2020
Flat 7	A (2015)	4th - 8th	3	100	4	11/07/2019 – 27/12/2019
Flat 8	A (2015)	4th - 8th	3	100	4	12/07/2019 – 10/01/2020
Flat 9	A (2015)	ground - 3rd	3	100	4	18/07/2019 – 07/01/2020
Flat 10	A (2015)	4th - 8th	3	106	4	08/07/2019 – 23/12/2019
Flat 11	A (2015)	9th - 13th	1	50	1	12/07/2019 – 27/12/2019
Flat 12	B (2006)	4th - 8th	1	49	2	09/07/2019 – 27/12/2019
Flat 13	B (2006)	ground - 3rd	2	65	1	15/07/2019 – 27/12/2019
Flat 14	B (2006)	4th - 8th	2	65	2	17/07/2019 – 27/12/2019
Flat 15	B (2006)	ground - 3rd	1	46	2	15/07/2019 – 27/12/2019
Flat 16	B (2006)	9th - 13th	2	59	1	15/07/2019 – 27/12/2019
Flat 17	B (2006)	9th - 13th	1	46	1	16/07/2019 – 27/12/2019
Flat 18	B (2006)	9th - 13th	2	59	2	22/07/2019 – 27/12/2019

It should be noted that during the pre-trial phase of the monitoring, before any equipment was installed in participants' homes, all of the sensors, transmitters, and PAPs were placed in flats that were not to be included in data collection for the main study. This allowed the researchers to troubleshoot any issues with data collection, sensor operation, signal loss, device operations, etc. During this pre-trial phase it was determined that the fan noise from the air quality sensor was too disruptive to occupants' sleep. It was decided, for this reason, that to reduce non-compliance and dropouts of participants, the air quality sensors that used fans to collect air samples would not be placed in the bedrooms, but rather in adjacent rooms. On-board $PM_{2.5}$ sensors were installed in the PAPs located in the bedrooms.

After testing the onsite transmission signal strength, all 18 flats were allocated to 11 Eltek Squirrel SRV250 data loggers. This architecture enabled real-time data collection from each flat to be sent to and stored on an online server every 5 mins using available 3G networks. Due to the availability of a constantly updated database, a core part of data quality assurance work was automated to check for power-off, signal loss, or other issues. Problems were quickly identified, and the appropriate action was taken to minimise data loss to the greatest extent. The Eltek indoor air quality transmitters, AQ110/112, were placed at a height of 1.5 - 1.7m above the finished floor in the living room of each flat to avoid disruptions in occupants' use of their homes. Eltek GD47B sensors were located at the same height in the bedroom where the PAP was used to measure air temperature, relative humidity, and CO_2 (Figure 3-3).

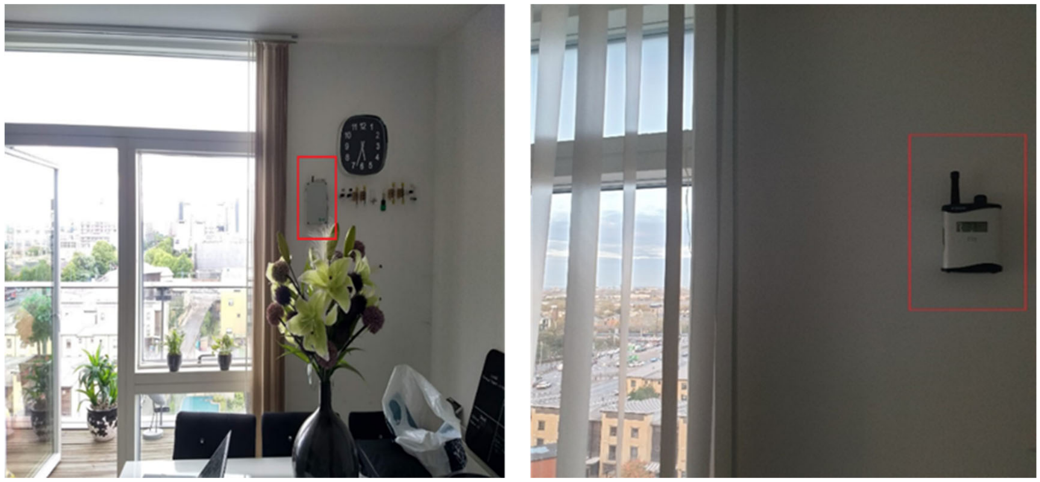

Figure 3-3 AQ110 (left) installed in a living room, GD47B (right) installed in a bedroom

An additional AQ110/112 sensor was deployed outside of each building to measure the real-time outdoor environmental pollutant level. Crilley et al. (2018) previously described the use of these optical particle sensors for ambient air quality monitoring and found that when properly calibrated and adjusted for relative humidity they are adequate for the assessment of airborne particle mass concentrations. The buildings were all located in relatively dense urban mixed-use areas adjacent to high traffic roads. A summary of parameters for these sensors can be found in Table 3-4 below.

Table 3-4 A summary of monitored parameters and resolution of the Eltek AQ110 sensors

Parameter	Sensor	Range	Resolution	Accuracy
Temperature	Thermistor	-30.0 to 65.0°C	0.1°C	±0.2°C at 20°C ±0.4°C for -5 to 40°C ±1.0°C for -20 to 65°C
Relative Humidity	Capacative	0.0 to 100.0%	0.10%	±2% RH (0 to 90% RH) ±4% RH (0 to 100% RH)
CO_2	Non-dispersive infra-red (E+E Electronik)	0-5000ppm	1ppm	<±50ppm, +3%
Particulate Matter PM_1 (≤1μm)	Optical Particle Counter (Alphasense OPC-N2)	0.00 to 500.0 μg/m^3	0.01 μg/m3	
Particulate Matter $PM_{2.5}$ (≤2.5 μm)	Optical Particle Counter (Alphasense OPC-N2)	0.00 to 500.0 μg/m^3	0.01 μg/m3	
Particulate Matter PM_{10} (≤10.0 μm)	Optical Particle Counter (Alphasense OPC-N2)	0.00 to 500.0 μg/m^3	0.01 μg/m3	
Airflow	-	0.00 to 500 ml/s	0.01 ml/s	
NO_2	Electrochemical (Alphasense NO2-A43F)	0.00 to 3.0 ppm	0.1 ppb	
CO	Electrochemical (Alphasense CO-A4)	0.00 to 300.0 ppm	0.01ppm	
TVOC	Photoionization detector (Alphasene PID-AH2)	0.00 to 50.0 ppm	10ppb	

3.4.2 Occupancy sensing

Passive infrared (PIR) sensors were installed in the middle of the ceiling in both bedrooms and living rooms of monitored flats. Pets were not allowed in the flats, which reduced the possibility of false positive detection results in unoccupied flats. Due to inherent limitations of sensors, the PIR data were analysed in combination with CO_2 data to more accurately determine if someone was present. This pairing of data worked well because the weaknesses of each of the two data types exhibit little overlap. For example, PIRs can only sense people in motion, but for CO_2 sensors there is a time delay in concentration change attributable to changes in occupancy. All monitoring data was collected from each sensor unit and then transmitted to a local data logger (Eltek SRV250 (Ashmore & Dimitroulopoulou)). The collected data was sent instantly from the logger to our password-protected Amazon cloud server using a separate 3G network. Images of some of the sensors used in the monitoring are shown in Figure 3-4.

Accurate assessment of the occupied state of flats was important for several reasons including the analysis of PAP use, interpretation of changes in $PM_{2.5}$ concentrations, and for parameterisation of the health impact model.

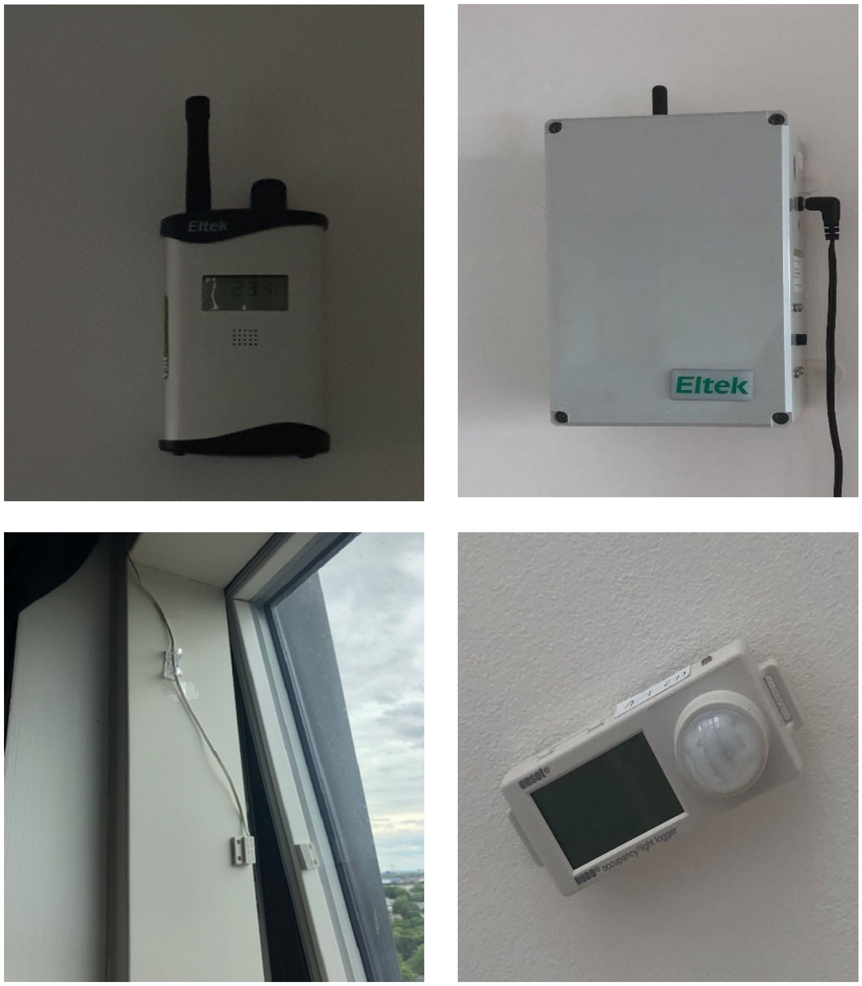

Figure 3-4 Photos of sensors (Eltek GD47B (top left), IAQ sensor (top right), window sensor (bottom left) and PIR sensor (bottom right))

3.4.3 Window operations monitoring

Window state (open/closed) was monitored in each flat to assess the impact on air purifier performance. Eltek GS34 window sensors (seen in Figure 3-5), using magnetic reed switches to monitor the status of openings were installed on balcony doors and windows in living rooms and bedrooms in all dwellings.

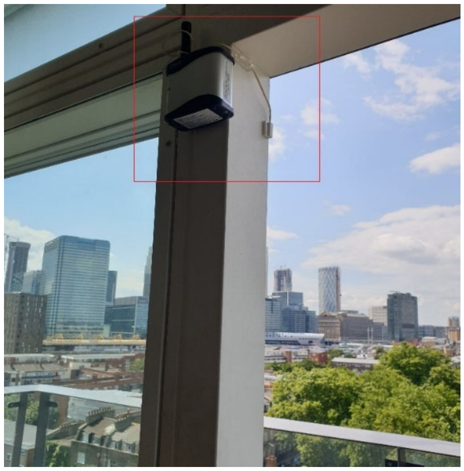

Figure 3-5 A typical installation of an Eltek GS34 at a balcony door in London

Two, functionally equivalent to the Eltek G34, standalone sensors Easylog EL-USB-5+ (Delgado et al.) were used in two bedrooms because they store data on the device, and connection to the loggers was poor. Two windows were permanently sealed, so 42 windows were monitored from 16 flats in total. The deployed window sensors did not capture the opening angle of the windows and doors, but additional information was collected through interviews with participants and the researchers' observations during the installation phase. There was a safety restrictor design in all monitored windows such that these hinged windows could only be opened to a rather limited distance. All residents confirmed that the windows were typically fixed in that maximum-opening position whereas doors were usually left fully open when opened.

3.5 Portable Air Purifiers

Philips, a study partner, loaned each household a Philips AC5659/10 home air purifier for use in the main bedroom during the study period (at no cost to the occupants). Identical PAPs were employed in all of the flats in London. The devices used in this study were similar to other models available on the market, in terms of capacity and method of filtration. The PAPs had a pre-filter, an activated carbon filter, and a HEPA filter with a clean air delivery rate (CADR) of 500 m^3/hour with a 0.3μm particle removal efficiency of 99.97%, for room sizes up to 60 m^2. The devices were fitted with internal $PM_{2.5}$ sensors that allowed for the purifiers to operate on an automatic mode that adjusted to the level of measured particulate matter. Additionally, each PAP had five operational modes described in Table 3-5 below.

Table 3-5 PAP modes with flow rates and clean air delivery rate (CADR)

Mode	**Flow (m^3/hr)**	**CADR (m^3/hr)**
Sleep	117.6	115
Mode 1	210.8	207
Mode 2	308.7	303
Mode 3	416.8	408
Turbo	509.8	500

The built-in sensor in each device for measuring $PM_{2.5}$ sent information via the cloud to the manufacturer of ON/OFF status, operational mode (e.g., fan speed), and $PM_{2.5}$ levels. To avoid sleep disturbance due to noise from the sensors, the Eltek AQ110 $PM_{2.5}$ sensors were installed in all dwellings in a room adjacent to where the PAP was situated, typically the living room.

The PAPs were placed in the main bedrooms where the window states were also recorded to monitor any influence of PAP use on occupants' use of windows. All PAP operation information was automatically stored in the password-secured cloud server of the device manufacturer with participants' consents. There were a number of different working modes with varying fan speeds (see Table 3.5), but for the purposes of this research, PAP status is simplified to either 'On', referring to the PAP working status regardless of specific fan speed, or 'Off'. More details of the PAP study can be found in a previous publication (Cooper et al., 2021a). Note that the PAP was provided for participants from July 2019 till the beginning of 2020.

3.6 Statistical analysis

Summary statistics (means, medians, ranges) were generated for $PM_{2.5}$, indoor and outdoor temperature and relative humidity (RH) using the open source statistical software R (R Core Team, 2018). (Where tests of statistical significance and correlations were used in the analysis of specific results they can be found in the captions of the associated figure or table).

3.7 Summary

In summary, 18 flats in London equipped with PAPs for approximately six months were continuously monitored for several indoor air pollutants, including $PM_{2.5}$, as well as for RH, temperature, and CO_2. In addition to the monitoring of indoor environmental conditions, outdoor air pollutants, temperature and RH were also monitored at each building site. The operating status, ON/OFF and fan speed, and changes to the status of the PAPs was recorded. Window operations and occupancy of the flats was also monitored over the same period.

Air quality monitoring was designed to answer questions about the effectiveness of reducing the $PM_{2.5}$ concentration in the bedrooms in which the PAPs were placed. Although similar studies have been done in the past, the work of this thesis monitored residences for much longer than in previous studies. In addition to the length of the monitoring period, indoor and outdoor measurements of environmental parameters were taken, whereas many other studies relied upon outdoor data from third-party sources off-site. Another novel approach used in this thesis was occupancy sensing and monitoring of window operations which was used to help inform interpretation of PAP use patterns, and other modelling work. In the following section, the results from the monitoring will be presented.

Chapter 4 Results – Air Quality Monitoring

4.1 Outline

This chapter is divided into two main sections, the first on outdoor air quality results from monitoring at the two east London sites (A and B) outside the study buildings at ground level. The use of on-site outdoor monitoring paired with indoor monitoring is one of the strengths of the work presented here. Much, if not most, previous research relies upon publicly available ambient air quality data from remote monitoring stations which may not accurately reflect the actual ambient pollution level at the site, as local conditions can greatly influence pollutant concentrations (Pinto et al., 2004).

The second main section of this chapter reports on the findings on indoor air quality monitoring in the 18 flats, and is further divided into results from the bedrooms, where the PAPs were located, and the living rooms where most of the sensors were located (see section 3.4.1 for more information on sensor location).

Results from both the indoor and outdoor air quality monitoring are then summarised in the final section.

4.2 Outdoor air quality

An examination of the outside air in the area of the monitored sites indicates when, where, and what type of, pollutants are of concern. Monitored ambient air quality is available over a full year, from both a nearby roadside station (Tower Hamlets – Roadside: 600m north) and urban background (Sir John Cass School: 2km West). Annual mean concentrations of both roadside and urban background $PM_{2.5}$ (13.2 μg/m^3 and 12.2 μg/m^3 respectively) breach WHO limits. Short-term 24-hour limits for background $PM_{2.5}$ were breached 23 times in 2019. Averaged daily and monthly concentrations for $PM_{2.5}$ for both London sites are shown in Figure 4-1, where morning and evening peaks in traffic can be observed as well as variation across the year.

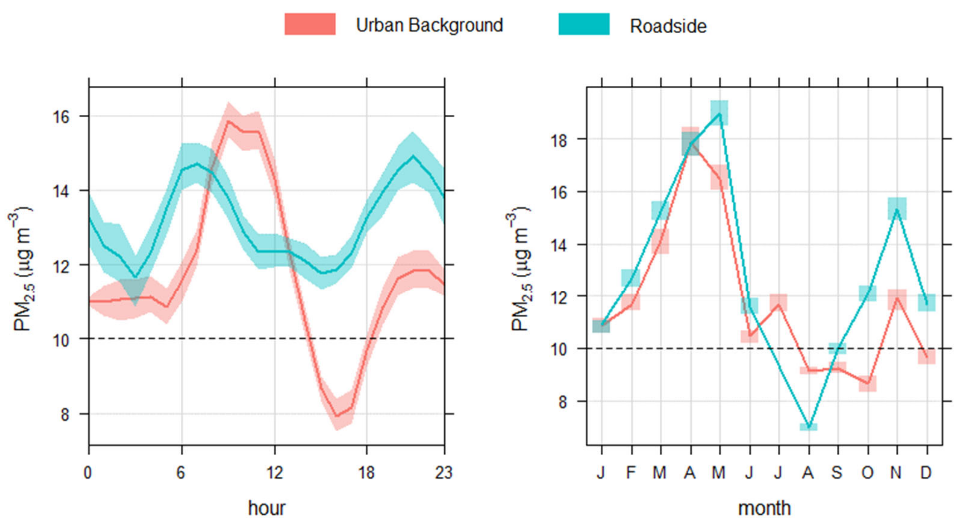

Figure 4-1 Annual ambient pollution levels at local London sites. Mean values are shown alongside 95% confidence intervals

On-site weather stations reveal outdoor sources of pollution. Using the OpenAir package for the statistical software R (R Core Team, 2018), a 'pollution rose' was created for each site. These diagrams, which can be seen in Figure 4-2 and Figure 4-3, illustrate the frequency distribution of wind direction temporally correlated with $PM_{2.5}$, very much like the commonly use wind rose, but with the information filtered by a chosen pollutant. At site A, $PM_{2.5}$ is from more local sources, potentially from a large building site adjacent to the apartments to the east (Figure 4-2).

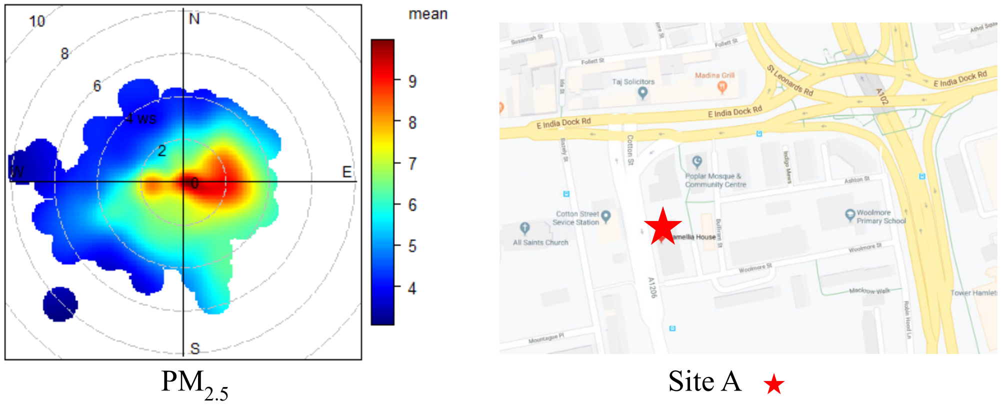

Figure 4-2 Direction and frequency of outdoor pollution sources at London site A. $PM_{2.5}$ is shown to mainly be from local sources to the east.

At site B, $PM_{2.5}$ has a local source of unknown origin to the north, as well as more distant sources to the south (Figure 4-3).

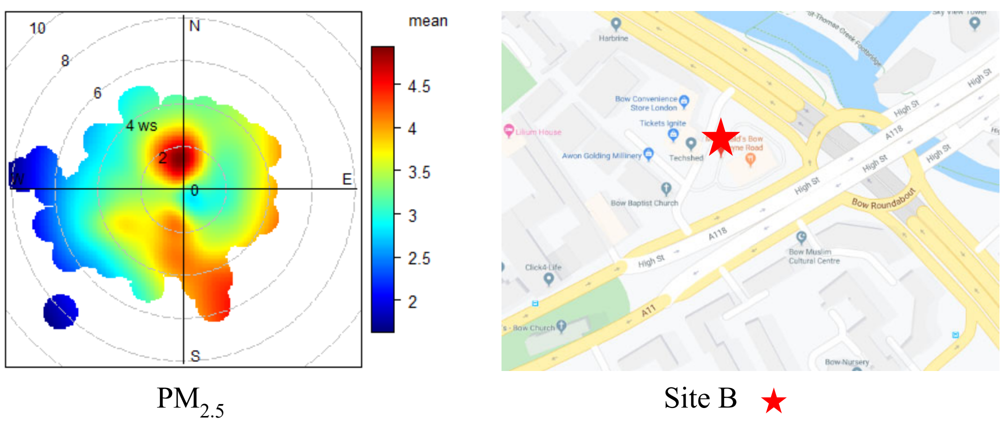

Figure 4-3 Direction and frequency of outdoor pollution sources at London site B. $PM_{2.5}$ is shown to mainly be from local sources to the north

The typical daily patterns of $PM_{2.5}$ in living rooms and outdoor concentrations illustrate the daily dynamics between indoor and outdoor sources, as well as when the internal generation of pollutants may occur (Figure 4-4). This figure shows average hourly values across a day, aggregated for all days and all apartments for the two London developments. Particulate matter levels outside at both sites peak around 8 am, most likely associated with peak morning road traffic, before dropping in the afternoon, with a slight rise during evening rush hour. Indoor levels at site B show a morning peak correlating with outdoor levels, and a large evening peak attributable to cooking activities. Site A concentrations are relatively flat throughout the day with a small evening increase that persists into the night. The reason for the high levels at night are not entirely understood, but could be explained by the outdoor sensor's adjacency to a road with atypical traffic patterns (e.g., evening deliveries), or to site conditions that trap particulates (the sensor was inside a mechanical room with door vents).

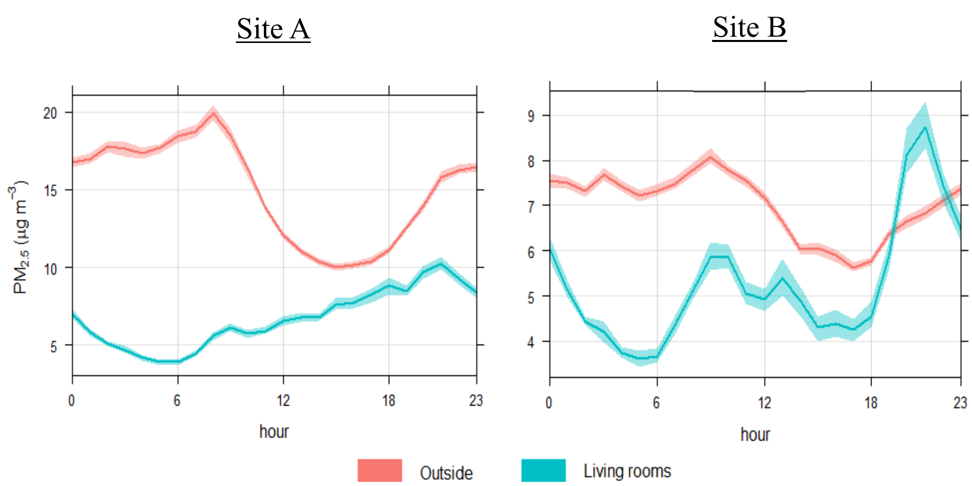

Figure 4-4 Aggregated (typical daily patterns) of outdoor and indoor $PM_{2.5}$ from sensors in each flat and outside of each building - site A left, site B right

4.3 Indoor air quality

This work focussed on the indoor air quality in homes using air purifiers. Homes monitored during the study period had good air quality when measured against WHO limits. There were, however, few times or days during the study period where outdoor air exceeded the limits. A running 24-hour mean of $PM_{2.5}$ exceeded WHO 24-hour limits on two occasions in indoor levels, accounting for less than 0.1% of total monitored hours. In outdoor levels, the WHO limit was exceeded on two occasions at each site, but this was still less than 1% of the total hours.

Indoor temperatures ranged from a high near 30°C to a low of nearly 17°C (Figure 4-5). Correlations between temperature, or relative humidity (Figure 4-6), and $PM_{2.5}$ were generally very weak, with Pearson's correlation factors all below +/ 0.5.

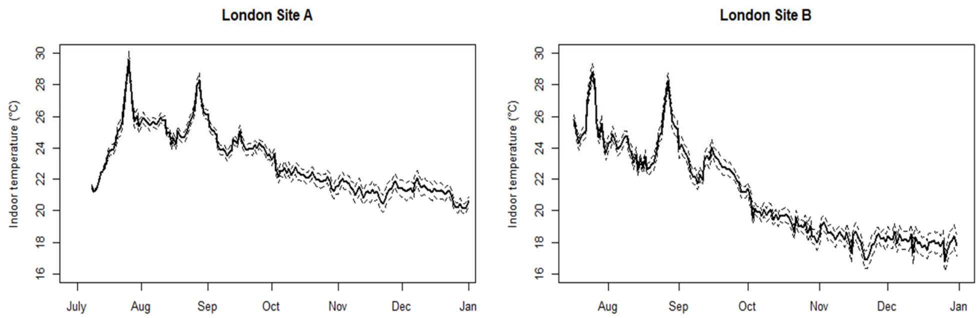

Figure 4-5 Indoor temperature across study period for each site. Solid lines are the daily means, and dashed lines are 95% confidence intervals

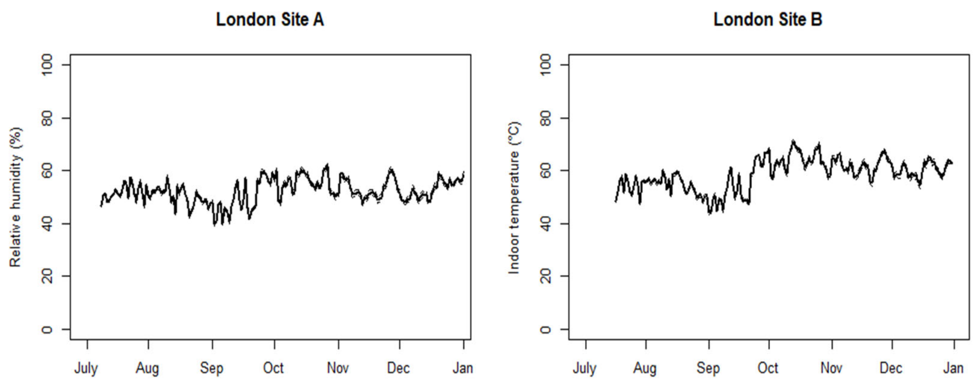

Figure 4-6 Indoor relative humidity (RH) across study period for each site. Solid lines are the daily means, and dashed lines are 95% confidence intervals

Mean $PM_{2.5}$ concentrations in the living rooms of flats at each site over the monitored period are shown in Figure 4-7 below. Concentrations showed little seasonal variation compared to the diurnal changes seen in Figure 4-4. Of the two sites, Site A showed the greatest change between the non-heating and heating season. Higher concentrations were observed in the heating season, even though Site A flats were equipped with MVHR systems intended to be operated in the heating season. However, the higher $PM_{2.5}$ concentrations did coincide with a reduction in measured window opening.

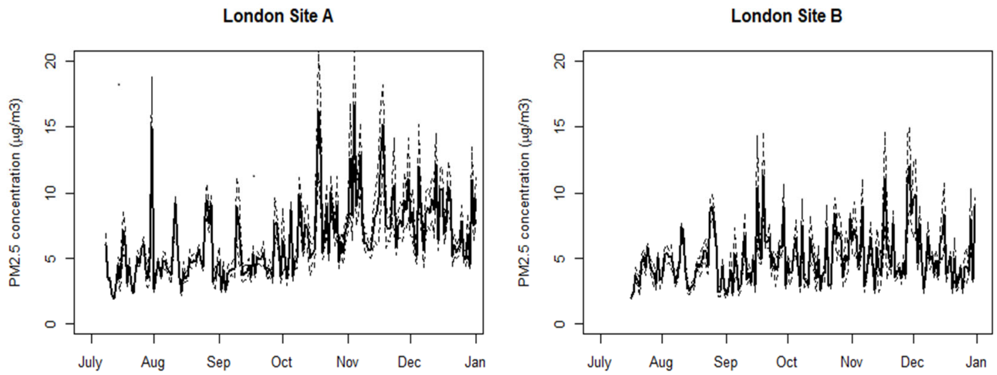

Figure 4-7 Indoor $PM_{2.5}$ concentrations across study period for each site. Solid lines are the daily means, and the dashed lines are 95% confidence intervals

Figure 4-8 and Figure 4-9 provide further detail into the monthly patterns of indoor $PM_{2.5}$ concentrations at all flats at the two sites.

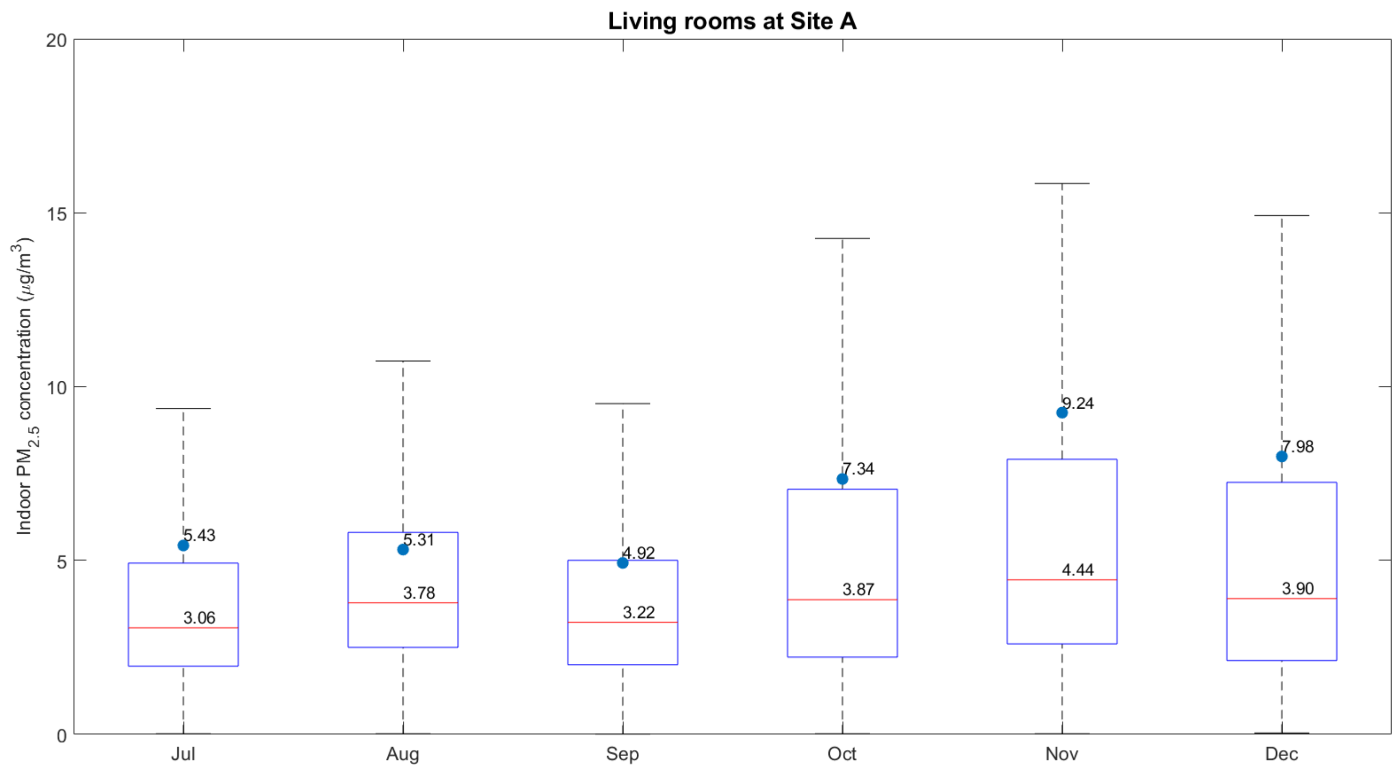

Figure 4-8 Mean, median and range of indoor $PM_{2.5}$ concentrations in Site A living rooms across the study period. Means are shown as blue dots, medians as red lines. PAPs were located in an adjacent room (main bedroom)

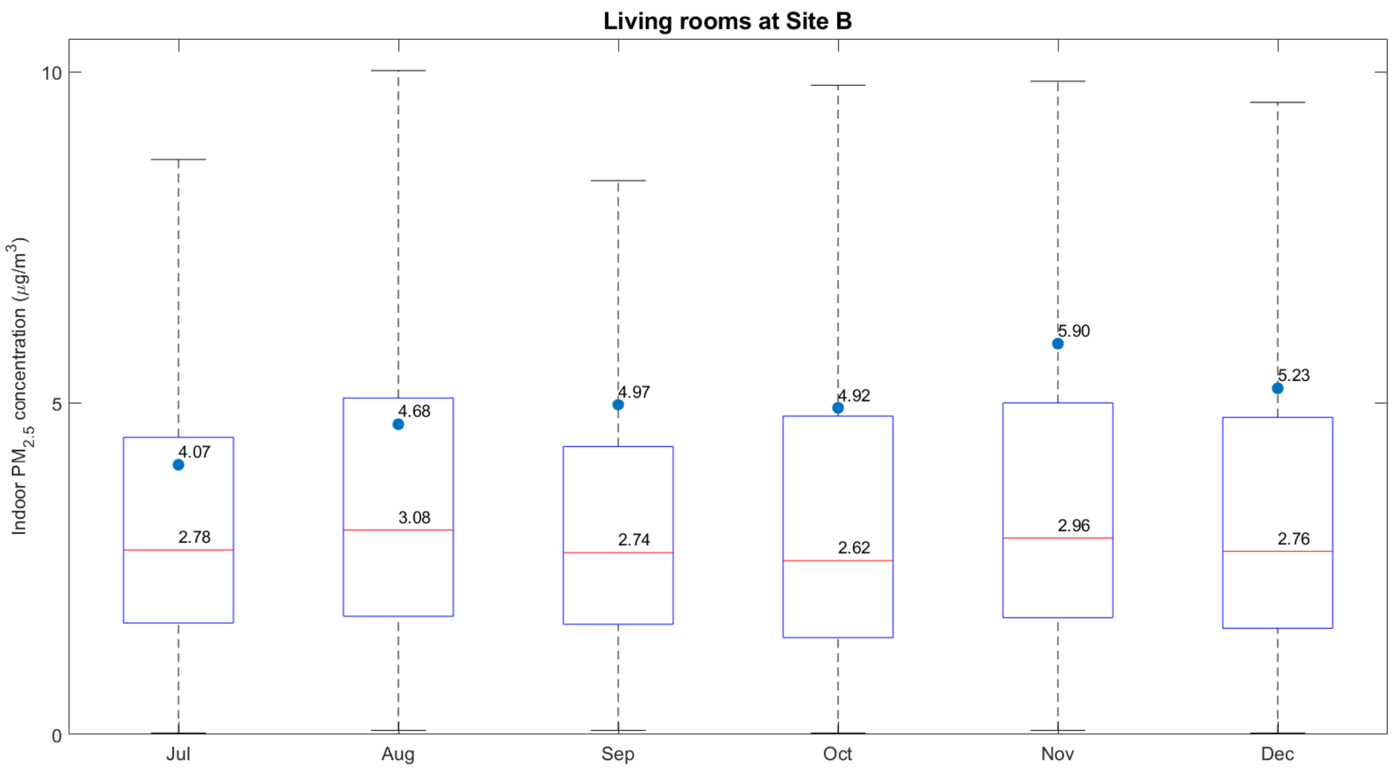

Figure 4-9 Mean, median and range of indoor $PM_{2.5}$ concentrations in Site B living rooms across the study period. Means are shown as blue dots, medians as red lines. PAPs were located in an adjacent room (main bedroom)

4.3.1 Impact of PAP use

4.3.1.1 Living rooms

The air quality in the living rooms of London homes using air purifiers in the bedroom exhibited a reduction in mean concentration with a small drop in peaks. Although modest, this reduction was statistically significant (*$p<0.001$*) based upon the non-parametric Kruskal-Wallis test. A non-parametric test was used due to the skewed distribution of pollutants. Figure 4-10 below illustrates the differences in $PM_{2.5}$ concentrations in living rooms with the air purifiers ON or OFF (in the bedroom). The mean concentration in living rooms with the air purifier OFF in the bedroom was 6.6 $\mu g/m^3$. The mean concentration in living rooms with the air purifier ON in the bedroom was 5.6 $\mu g/m^3$.

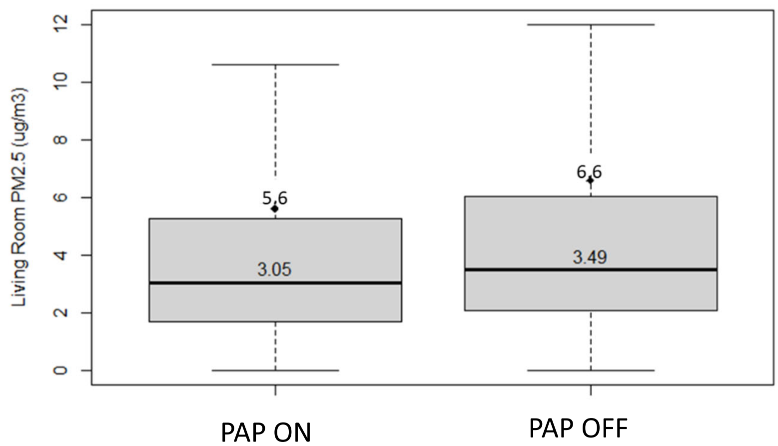

Figure 4-10 $PM_{2.5}$ concentration in living rooms of participants with air purifiers ON (any fan speed) or OFF with medians indicated by dark horizontal lines, means as points

4.3.1.2 Bedrooms

When measurements from all participant bedrooms are combined, a clear decay curve can be seen from the onset of PAP use to 100 minutes run time (Figure 4-11). When running with the windows closed, a median percentage reduction of 20% can be observed from initial concentrations after 30min. A similar reduction in $PM_{2.5}$ concentration was observed in cases of bedroom windows opened as well as closed. Window operations were important to understand due to potential drivers for PAP operation (e.g., temperature) and air exchange rates, as well as the indoor concentrations relative to outdoor sources of $PM_{2.5}$. Figure 4-11 represents the aggregated performance of the PAP, it is important to note that not all run cycles resulted in the same reduction pattern, particularly in the presence of continued internal sources, or re-suspension. From all run cycles, only 56% of cases experienced a reduction on initial concentrations after 30 minutes. Similarly, a reduction of 50% on initial concentrations was observed after 60 minutes of PAP operation in 45% of run cycles.

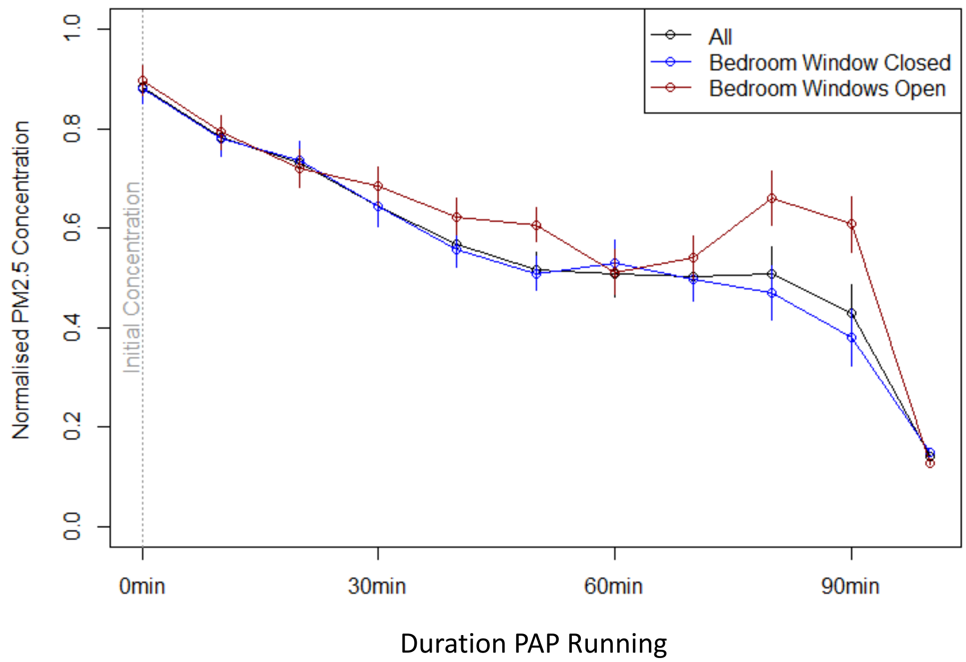

Figure 4-11 Change in the mean concentration of $PM_{2.5}$ in London bedrooms using home air purifiers. PAP switched ON at time 0, with minutes of run time shown. Vertical bars represent the standard deviation of the mean across all flat flats

Normalised concentrations were used in the bedrooms because the sensors internal to the devices could not be fully calibrated. However, calibrated sensors collocated with the PAPs were in strong agreement with the levels measured by the air purifiers (R^2 = 0.9, RMSE = 4.5 µg/m^3, MBE = -0.16 µg/m^3). The normalised $PM_{2.5}$ concentration in the bedrooms of all flats is shown in Figure 4-12. Technical specifications that include CADR (Clean Air Delivery Rate) by fan speed are shown in Table 3-5.

Hourly patterns indicate that the concentration of particulate matter is correlated with fan speed. That is, the higher the fan speeds the lower the concentration of $PM_{2.5}$ as is illustrated in Figure 4-12.

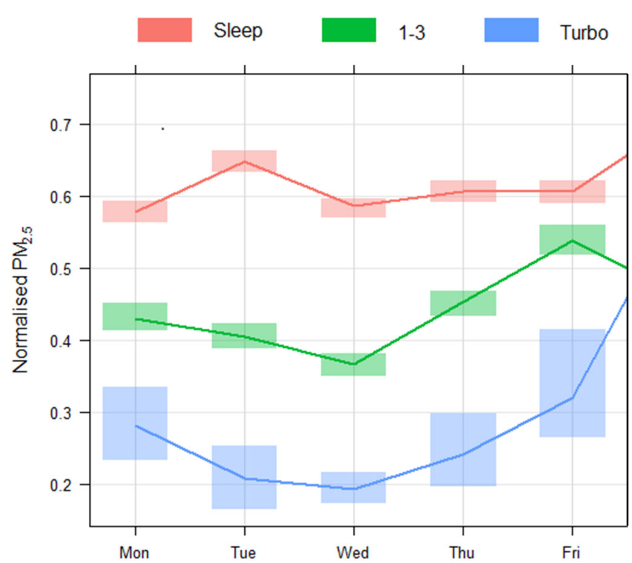

Figure 4-12 Changes in the concentration of $PM_{2.5}$ (normalised by the mean) in bedrooms during a typical work week under different PAP operational modes. Refer to Table 3-5 for PAP specifications

4.4 Summary

Indoor and outdoor air quality was monitored for approximately 6 months, a much longer period than in previous studies, and daily and seasonal changes in $PM_{2.5}$ were measured. The indoor air quality of the flats that were monitored in London in 2019 was generally very good relative to the guidelines set by the WHO. The monitored flats were in modern, well-sealed, energy-efficient buildings which could explain why the indoor $PM_{2.5}$ levels were generally lower than outdoor levels. Those peaks that exceeded recommended values were typically associated with indoor source generation, primarily cooking. Irrespective of the $PM_{2.5}$ concentrations, however, the PAPs were effective at reducing levels in the rooms in which they were operating by a mean of 45% after 90 minutes of operation. This level of reduction is in line with the findings from many of the studies identified in the literature review, and provides further evidence of the effectiveness of PAPs in real-world conditions, across seasons, and with different $PM_{2.5}$ concentrations.

Chapter 5 Methods – Qualitative Approaches

5.1 Outline

This chapter introduces the survey tools and qualitative analysis that were utilised in the study to gain an understanding of several aspects of occupants' health and wellness, perceptions, and opinions of the air quality at their home, and behaviours with regard to portable air purifiers. The chapter gives a brief background on some of the motivations for including qualitative methods in the work, followed by a description of the crossover design of the study. Then it provides a description of the semi-structured interviews and surveys employed in the work. Finally, it presents a brief summary of the strengths and weaknesses of the methods used.

5.2 Background

The built environment is made up of complex relationships, both synergistic and discordant, between the physical, contextual, and personal domains. Qualitative methods of research allow for a fuller interpretation of empirical findings within the human context. Therefore, the addition of surveys and interviews can add meaning to the measured quantitative parameters and value to modelling. In this work, several assessment methods and tools were used to gather information about occupants' behaviours and perceptions, and to parameterise the health models more accurately.

The research involved healthy adults. Informed consent was sought and required from all participants. Although data were anonymised, a small risk of identification of participants due to the small number of participants was noted as a potential issue. To help mitigate this potential, each participant was assigned a unique code, which was kept separately from questionnaire results. All data was stored in a password protected laptop, as described in the relevant Data Protection Application document (see Appendix D).

Interviews and questionnaires were developed with the minimum number of questions to collect necessary health information relevant to the study of indoor air quality, and the potential effects of air purifiers and personal behaviour on exposure to air pollution. All participants received information sheets that explained the research, their role in it, and that they had the choice to discontinue participation at any time without reason or penalty. All participants signed a letter of consent to participate. Copies of the information provided to the participants, as well as full versions of the surveys and the semi-structured interview scripts, can be found in Appendices C and D.

5.3 Cross-over study design and motivations

A cross-over structure was applied in the study to answer research questions regarding the performance of the home air purifier with respect to $PM_{2.5}$ indoors, and to provide information about patterns of use, potential correlations with other environmental factors or personal characteristics. This approach to the study was also designed to answer different questions posed as part of the Quasimodo project which are not applicable to the work of this thesis, and therefore will not be discussed here. There were three crossover tracks, and one group which was allowed to use the PAP without any restrictions throughout the study period. The groups are described in greater detail below.

5.3.1 Crossover Tracks

The participants were divided into four (4) roughly equal tracks, one group which could use the PAP as they wished for the duration of the study, and three with alternating configurations of PAP use as summarised above, shown in Table 5-1 below, and described in greater detail in section 5.3.2. Each phase of the crossover period lasted a minimum of three weeks. For one week of each phase, participants were sent short surveys at the end of each day that asked them about the quality of their sleep and wellbeing during the previous day.

Table 5-1 Crossover tracks, each period lasted a minimum of three weeks.

No. of apartments	First period (13/08/19-03/09/19)	Second period (03/09/19-24/09/19)	Third period (24/09/19-15/10/19)
4	PAP ON	PAP ON	PAP ON
4	PAP ON	PAP OFF	PAP SLEEP
5	PAP SLEEP	PAP ON	PAP OFF
5	PAP OFF	PAP SLEEP	PAP ON

5.3.2 PAP Settings

PAP ON

The air purifier was switched on and participants could change the settings (e.g., turn-off, change fan speed, etc). The air purifier was installed in their home, and they could use it according to their own preferences. They could do the following in these 3 weeks:

- Turn the air purifier on
- Turn the air purifier off
- Select any airflow setting: Settings are “sleep” setting SL (lowest airflow), fan speed 1 (low), fan speed 2 (medium), fan speed 3 (high), turbo setting (maximum airflow), or automatic airflow.

PAP OFF

The air purifier was switched off.

PAP SLEEP

The air purifier was switched on to “sleep” mode for all three weeks. This is the lowest ventilator speed (refer to Table 3-5 for CADR of PAP modes).

The status of the PAP (i.e., ON, OFF, Fan Speed) was monitored via a cloud connection with the manufacturer. Compliance with crossover protocol was evaluated based on the actual operation of the PAP via data from the device itself. During data analysis participants were classified, and data were analysed, based upon the actual air purifier use.

5.4 Questionnaires and surveys

5.4.1 Semi-structured interviews

Semi-structured interviews for the collection of qualitative data are common in qualitative research. The approach consists of a conversation between the researcher and the participant guided by an interview protocol which can be supplemented by follow-up questions and comments. The method allows the researcher to collect open-ended data, to gather participants’ opinions about a particular topic and to explore more deeply the reasons behind their opinions or beliefs. When done well, semi-structured interviews can provide reliable, comparable, and meaningful qualitative data.

The semi-structured interviews used in this thesis were compiled using existing survey instruments selected because they had been used and validated in previous published studies. The specific surveys, or portions of surveys, that were used included, the SF-12, the PSQI, and the Building Use Studies (BUS). A brief description of each of these can be found in the following paragraph.

5.4.1.1 SF-12

The 12-item Short Form Survey, or SF-12, is a self-reported outcome measure assessing the impact of health on an individual's everyday life. The SF-12 is a shortened version of the 36-item Survey created to reduce the burden of responses on participants. The SF-12 uses eight domains to assess the impact of a participant's health on their everyday life. These domains include:

- Limitations in physical activities because of health problems;
- Limitations in social activities because of physical or emotional problems;
- Limitations in usual role activities because of physical health problems;
- Bodily pain;
- General mental health (psychological distress and well-being);
- Limitations in usual role activities because of emotional problems;
- Vitality (energy and fatigue); and
- General health perceptions.

The SF-12 was used without alteration from its original format or content in the semi-structured interviews.

5.4.1.2 The Pittsburgh Sleep Quality Index (PSQI)

The Pittsburgh Sleep Quality Index (PSQI) is a self-rated questionnaire which assesses sleep quality over a 1-month time interval. The questionnaire was developed by Buysse et al. (1989) for use with patients suffering from sleep disorders. However, it is now often used in the study of healthy adults. It is composed of nineteen items which, when analysed generate seven "component" scores: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. The PSQI was used in its entirety, without modification, so as to maintain the integrity of the scoring process which uses weighted values to responses to calculate the final scores. The sum of the scores from each of the seven components generates a single score. The lower the total score, the better rated the sleep quality.

5.4.1.3 Building Use Studies (BUS) Occupant Survey

The BUS occupant survey (Arup, 2020) is a post-occupancy questionnaire whose aim is to gather feedback from building users on their general satisfaction with different aspects of their home including conditions such as temperature, noise, lighting control, and overall comfort. In an effort to constrain the length of the interview to avoid interview fatigue, only a portion of the BUS was used the interviews conducted as part of the work presented here. Specifically, sections of the survey that were removed included questions about the satisfaction with residence overall (e.g., storage, location and layout), about noise levels within the residence, and about lighting quality. A copy of the survey as included in the semi-structured interview can be found in Appendix C.

5.4.1.4 Interview structure

The first part of the interview involved the collection of basic demographic information (e.g., age, gender, etc.), as well as questions about typical household activities that had the potential to affect indoor air quality, especially those involving $PM_{2.5}$ generation. The next set of questions was about the participant's motivation for volunteering to join the study. These questions were asked to try to understand the potential for self-selection bias, and to identify any pre-existing concerns the participant had regarding any of the following:

- air quality problems; and
- health/wellbeing concerns (for a particular household member or more generally); and
- specific interest in having the air purifier, and if so, for what reason.

Next, a section of the BUS survey (Arup, 2020) was used to determine the occupants' opinions on various aspects of the indoor environment of their home (Cohen et al., 2001). Occupants were asked to rate qualities of their home, such as the stillness of the air, the temperature of the air, noise intrusion, how much control they felt they had over different aspects of the home environment, and the overall satisfaction with the comfort. The semi-structured interview scripts, can be found in Appendix C.

Participants in the study were not selected based on any specific health condition, but specific conditions did not prevent people from participating. Volunteers were not asked to provide any documentation of health status, for example a note from their GP or a prescription, instead mental and physical health were self-reported using the UK

Short Form health survey (SF-12) (Jenkinson et al., 1997). Participants were also asked if they considered themselves to have any of five specific health conditions or symptoms frequently associated with air quality or lung function. These conditions included chronic obstructive pulmonary disease (COPD), hay fever or aero-allergies, frequent respiratory problems (including coughs, colds, or respiratory infections), watery/itchy eyes, and asthma. If participants responded yes to any of these, they were then asked if they were taking any medications or treatments for the condition(s), and to what extent they felt it affected their daily life. As with all of the questions asked in the interview, participants were always informed that their responses were completely voluntary, and any questions could be skipped without disqualifying them from participation. However, the response rate was high, with only one participant electing not to answer some of the SF-12 questions.

During the first visit, when the semi-structured interview took place, participants were also introduced to the use of the air purifier, and the other monitoring equipment was installed. Upon completion of the 9-week crossover study, another semi-structured interview was performed to investigate any effects on participants' sleep and wellbeing, to understand how the air purifiers were used, and to gather information about any change in occupants' perceptions of the quality of the air in their homes or bedrooms. After the cross-over study period, all 18 households agreed to continue with monitoring to the end of the calendar year. This extension allowed the capturing of data during the heating season.

5.4.2 Wellbeing and sleep quality surveys

During one week of each of the three crossover periods participants were sent via email a link to a further short survey hosted on the Qualtrics platform. The surveys asked the participants about the quality of their sleep and wellbeing, and if they felt that the quality of the air in their home influenced either. A copy of the survey is included in Appendix D.

5.4.3 Statistical analysis

The tests of statistical significance and correlations were generated using the open source statistical software R (R Core Team, 2018). BUS survey results were analysed through The Usable Buildings Trust, information about which can be found at the BUS Methodology website (Arup, 2020).

A logistic regression model was used to explore correlations between environmental parameters and PAP use. This type of model has been used to describe occupant behaviour related to window operations, and is a reasonable approach to discerning operational behaviour of binary actions (ON/OFF), and in this example in relation to temperature (Andersen et al., 2013). In this model, outdoor temperature was used as an explanatory variable to simulate whether the PAP was ON or not. The coefficients for this model are represented by the following expression, and are significant to the level of 0.05:

Logit (probability of PAP ON) = -2.83 + 0.082 * Outdoor Temperature

5.5 Summary

In summary, data were collected from all 18 participating flats on the characteristics of the homes, the buildings in which they were located, and the areas adjacent to the buildings (see Appendix D for the Building Characteristics Survey), In addition to the observations and information gathered by the researchers, semi-structured interviews were conducted with the primary participant (defined as an adult who slept in the bedroom in which the PAP was to be located) at the installation of the sensors and PAPs, and again at the end of the study period. In addition to the baseline and exit interviews, participants were sent, during the study via email, an invitation to complete a short survey on sleep quality and wellbeing.

Information gathered from parts of the semi-structured interviews, such as the BUS results, was invaluable in answering research questions about people's perception of indoor air quality, and associations between indoor environmental conditions and PAP use. In addition to the specific questions from the different survey instruments (such as the PSQI), many participants volunteered additional information in the comments sections that was useful in supplementing the pre-defined interview questions, and provided meaningful insights into participants' behaviour and motivations. Results from these comments, as well as from the interviews are provided in the following chapter.

Chapter 6 Results – Qualitative Analysis

6.1 Outline

This chapter is divided into two main sections that report on the results of the qualitative assessments described in chapter 5. The first section is on the perception of the quality of the air at home and consists primarily of results from the BUS survey. The second section presents the findings from an analysis of participants' reported observations about the PAPs' effects and the results from the BUS surveys, paired with the monitored operational status of the PAPs, and the measured environmental parameters.

6.2 Findings on sleep and wellbeing

6.2.1 Pittsburgh Sleep Quality Index (PSQI)

During the semi-structured interviews, participants were asked about their sleep quality using the PSQI (Buysse et al., 1989). Interviews were conducted when the PAPs were installed (baseline) and again at the end of the 9-week crossover period (follow-up).

Participants were found to have an average improvement in overall PSQI scores of 19%, with 17 of the 18 participants responding. Of the 17 respondents 59% reported some improvement in their sleep, ranging from 25 to 75% improved sleep quality. The medians and ranges are shown in Table 6-1 (improvement for this instrument is indicated by a *lower* number), and the same results are presented graphically in Figure 6-1. As can be seen in the table and figure, the medians remained the same between the two surveys, although the ranges decreased slightly. And, although statistically significant, these findings merely represent directionality in sleep improvement, and a longer study period with more participants is needed to determine if these subtle improvements are truly meaningful in terms of better sleep quality.

Table 6-1 Median range of PSQI score at baseline and follow-up among the study participants

	Baseline Median (range)	Follow-up Median (range)	P-value*
PSQI score	5 (2, 14)	5 (2, 9)	0.009

*P-value obtained from the non-parametric Wilcoxon Signed rank test

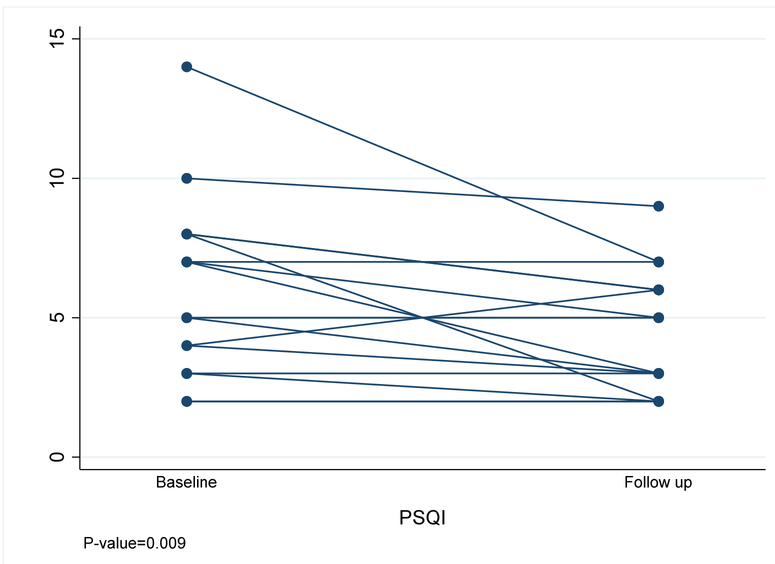

Figure 6-1 PSQI score at baseline and follow-up among study participants

The findings on the impact of wellbeing as measured by surveys, and semi-structured interviews did not suggest measurable improvements, nor did they reach statistical significance.

6.3 Perceived indoor air quality

Sections of the Building Use Studies Survey (Arup, 2020) were used to assess the satisfaction of occupants on a number of indoor environmental factors. Of the 22 factors that were scored, only three were rated as fully satisfactory: control over heating, control over lighting, and the stability of the temperature in winter. Eleven factors were considered marginal including: overall condition of indoor air in summer and winter, control over ventilation, the odour of air in the summer, and comfort overall. Notably, eight factors were rated unsatisfactory including: the humidity, stuffiness and stillness of the air in summer, the control over cooling, and the overall temperature in summer and winter. A list of parameters and scores is shown in Table 6-2 below.

Table 6-2 A summary of parameters and scores (upper and lower limits) from the Building Users' Survey (BUS)

Parameter (short name)	Parameter (long name)	Study mean score	Scale midpoint (limits)	Benchmark score (limits)	Study mean percentile	Scale midpoint percentile	% Dissatisfied
Airsdry	Air in summer: dry/humid	4.4	4 (3.8-4.2)	3.5 (3.3-3.7)	92	72	58
Airsfresh	Air in summer: fresh/stuffy	4.9	4 (3.7-4.3)	3.5 (3.2-3.7)	92	67	63
Airsodourl	Air in summer: Odourless/ smelly	3.4	4 (3.8-4.2)	2.6 (2.9-2.4)	76	94	37
Airsover	Air in summer: Overall	3.9	4 (3.8-4.2)	5.4 (5.1-5.6)	4	6	52
Airsstil	Air in summer: Still/draughty	2.4	4 (3.7-4.3)	2.8 (2.5-3.1)	27	94	79
Airwover	Air in winter: Overall	5.6	4 (3.8-4.2)	5.5 (5.3-5.7)	52	2	0
Airwdry	Air in winter: Dry/humid	3.3	4 (3.8-4.2)	3.3 (3.1-3.5)	52	77	42
Airwfresh	Air in winter: Fresh/stuffy	3.8	4 (3.7-4.3)	3.3 (3.1-3.6)	74	75	27
Airwodourl	Air in winter: Odourless/ smelly	2.5	4 (3.7-4.3)	2.8 (2.5-3.0)	40	91	5
Airwstil	Air in winter: Still/draughty	2.9	4 (3.7-4.3)	3.1 (2.7-3.4)	50	77	80
Comfover	Comfort: Overall	4.9	4 (3.8-4.2)	5.9 (5.7-6.0)	12	2	21
Cntco	Control: Over cooling	3.2	4 (3.7-4.3)	4.4 (4.0-4.7)	17	42	68
Cntht	Control: Over heating	6.5	4 (3.6-4.4)	5.2 (4.9-5.6)	81	17	0
Cntlt	Control: Over lighting	6.2	4 (3.7-4.3)	5.7 (5.4-6.0)	66	6	5
Cntnse	Control: Over noise	3.2	4 (3.7-4.3)	3.9 (3.6-4.2)	29	56	48
Cntvt	Control: Over ventilation	4.5	4 (3.7-4.3)	5.1 (4.8-5.4)	34	17	37
Tshot	Temp in summer: Hot/cold	2.4	4 (3.8-4.2)	3.3 (3.2-3.5)	11	79	69
Tsover	Temp in summer: overall	3.1	4 (3.7-4.3)	4.9 (4.6-5.1)	2	19	68
Tsstable	Temp in summer: Stable/variable	3.8	4 (3.8-4.2)	4.2 (3.9-4.4)	32	42	38
Twhot	Temp in winter: Hot/cold	4.6	4 (3.9-4.1)	4.3 (4.1-4.4)	82	16	32
Twover	Temp in winter: Overall	5.7	4 (3.8-4.2)	5.5 (5.3-5.8)	53	4	5
Twstable	Temp in winter: Stable/variable	3.4	4 (3.7-4.3)	3.8 (3.6-4.1)	24	46	37

Generally, occupants rated the indoor air quality poorer in the summer with a very high rate of dissatisfaction with the temperature, stuffiness and stillness of the air, as well as the control over cooling. Mean carbon dioxide levels measured in the flats were very often high, especially during the heating season in bedrooms (Figure 6-2). However, the highest rates of dissatisfaction with the air did not correspond with the highest levels of CO_2 (often associated with perceptions of stuffiness and air quality), but rather with higher temperatures in the summer, indicating it is unlikely to be perceived air quality that is driving occupants' (dis)satisfaction.

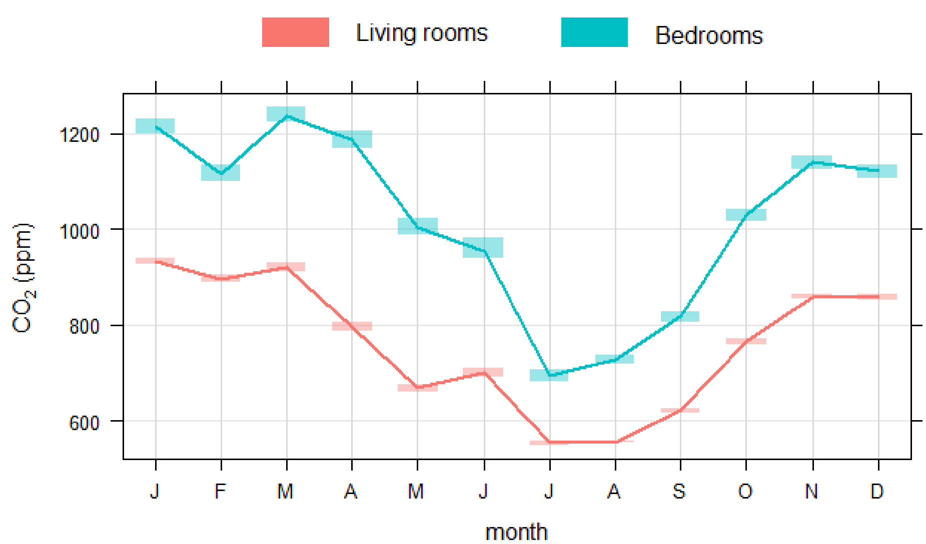

Figure 6-2 Mean CO_2 concentrations in living rooms and bedrooms throughout the year

6.4 PAP operation behaviour

Residents expressed dissatisfaction with the temperature in their homes in summer and commented in interviews that they appreciated the "cooling" effect of the PAPs, therefore, the pattern of use displayed is not illogical. There is a clear correlation between increasing temperatures and increasing PAP use as shown in the logistic regression model below (Figure 6-3) and supported by an absolute increase in the duration of air purifier use per day with increasing mean outdoor temperature shown in Figure 6-4.

In Figure 6-3, the blue circles are binary observations of PAP status (ON or OFF), and the green circles are the predicted probability of the PAP status based on outdoor temperature. Outdoor temperature was used in this analysis because in these non-air-conditioned flats, outdoor and indoor temperature are highly correlated at temperatures above about 18°C. Additionally, temperatures indoors rarely dropped below 16°C in any of the monitored residences. It is clear that the trend of PAP operating was noticeably greater with increasing outdoor temperatures (and commensurate indoor temperature). The model provides good statistical evidence for the anecdotal finding that participants' PAP use is driven by the perceived cooling effects of the devices.

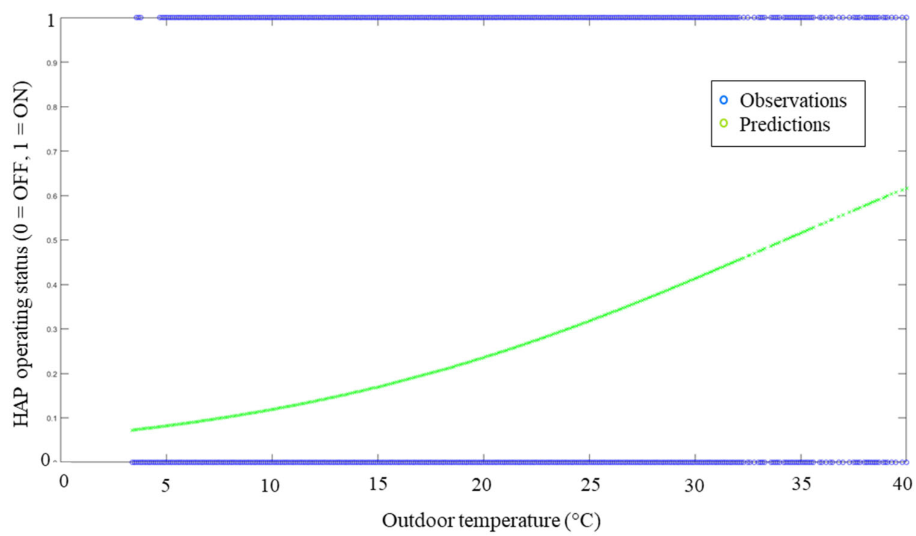

Figure 6-3 Probability of air purifier use in in relation to mean outdoor temperature ($p<0.001$)

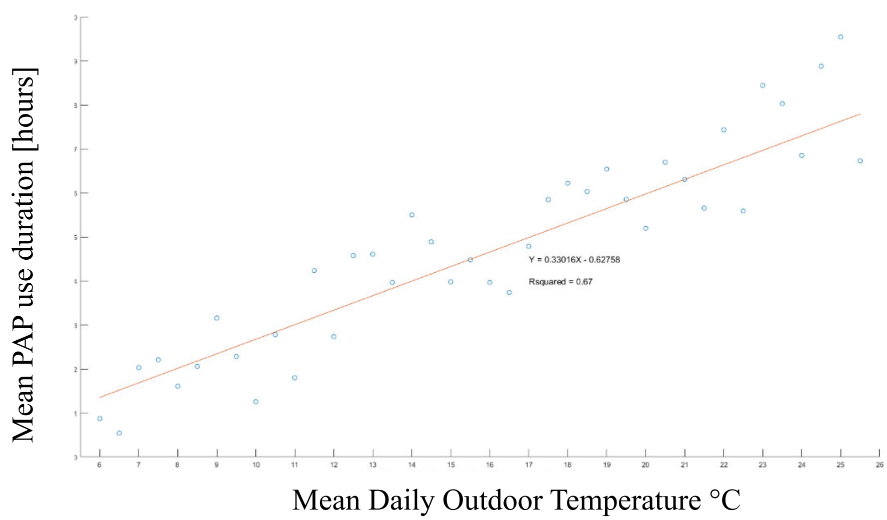

Figure 6-4 Mean air purifier use in relation to mean outdoor temperature ($R^2 = 0.67$)

The pattern of use over time could be due to the normal seasonal drop in temperature (Figure 6-5). However, it could have also been attributable to study "fatigue" or from a loss of interest in the device. There is a peak in use at the start of the study, perhaps related to a "new gadget" being introduced into the home, and then use slowly declines (with peaks that may correspond to directives of the crossover periods or periods of warm weather) into the cooler autumn and winter months. From interviews, people generally expressed more satisfaction with the overall air quality and comfort in the cooler months which could contribute to a decline in the perceived utility of an air purifier. Additionally, many residents reported that they believed the PAP cooled the room in which it was operating, and this may have been undesirable as temperatures dropped. During the crossover period of the study, when participants were instructed to use the PAP in any manner of their choosing, they used the PAP a mean of 19.2 hours per day, however most of that time (14.2 hours) the devices were set to the lowest fan setting (SLEEP) which may have been considered as a 'standby' mode and as previously demonstrated, has a lower impact on particulate concentrations (Figure 4-12). During the crossover period, PAPs were used primarily on the lowest fan speed (SLEEP), and used on any higher fan speed a mean of only 3.7 hours per day. Additionally, people interacted with the devices less often after the crossover period was complete, modifying the settings a mean of 5.1 times a day during the crossover, but only 3.0 times after. Ultimately, across all free-use periods the PAP was ON a mean of 15.6 hours per day.

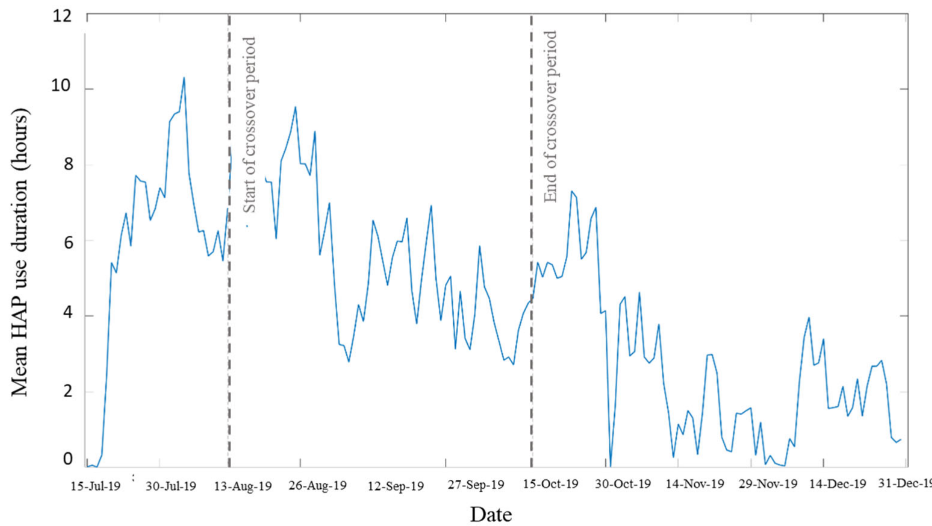

Figure 6-5 Change in PAP utilisation (hours per day) over the course of the study period excluding SLEEP mode. The crossover portion of the study is bracketed by the vertical dashed lines

Another possible motivation for PAP use could have been occupant health and wellbeing. Healthy adults were recruited, but having specific health conditions did not exclude people from participating. Fifteen of the participants reported having allergies and/or itchy and watery eyes, 4 people reported having asthma, 3 reported frequent respiratory infections, and 1 participant had COPD. Only three participants reported no symptoms of allergies, asthma, frequent respiratory infections, or COPD. If a correlation were observed between health concerns and PAP use, time- and temperature-related trends, as were observed would be unexpected (unless associated with seasonal allergies). Instead, more likely to be observed would be a low-use group and a high-use group correlated with health status. However, no correlation was observed between participants that reported having some type of condition that may be associated with air quality and PAP use, and temperature remains the one factor with a clear relationship to use.

Thermal stimuli affect the way that occupants experience comfort and control of their environment indoors. A review by Day et al. (2020) provides a good description of the way in which occupants interact with different components of the built environment and the drivers behind those behaviours. Thermal comfort is explored as an occupant motivation for window operations and thermostat use in the Day et al. review, and is further explored in work by Calì et al. (2016) and by Jeong et al. (2016), among others. Very little work was found that included occupant interactions with building environmental controls other than windows and thermostats. One study by (Rijal et al., 2008) developing adaptive algorithms that included the operation of fans to predict thermal comfort, and noted that increased mean globe temperatures were associated with more fan use. The results from Rijal et al. (2008) support the supposition that thermal comfort is an important driver of PAP operation. This finding paired with monitored PAP operational behaviour, provides important evidence regarding the real-world use of PAPs that can inform future modelling.

6.5 Summary

The evidence for any effects of PAP use on sleep was weak, and additional work to further examine any association would be a part of future work. A larger sample size, the use of a sham device, and the addition of user diaries would help clarify any potential effects.

Perhaps the most relevant findings for understanding some of what motivates occupants to use PAPs were from the BUS survey and informal interviews. That is, the importance of thermal conditions and comfort rather than perceptions of the quality in occupants' decisions to use PAPs. Although the PAPs did not have any cooling capacity, occupants still reported they felt a cooling effect from the devices. It may be that occupants perceived air movement from the device’s internal fan and associated that with a cooling effect. And, given that occupants expressed significant dissatisfaction with the high temperatures during the non-heating season, it is perhaps unsurprising occupants used the PAPs more during periods of warmer indoor temperatures.

Chapter 7 Methods – Health Modelling

7.1 Outline

This chapter comprises eight sections (including the outline) that introduce the health impact modelling methods that were used to estimate the impacts using PAPs indoors for the reduction of $PM_{2.5}$. Section 7.2 provides the context for health impact modelling more generally whilst the second section is a description of the model used in this thesis. Model parameterisation is described in the next section to define the central scenario used in the assessments. The subsequent section provides analyses of some of the uncertainties that can arise in any type of modelling. In the case of this health impact assessment, three different tests are run to determine where sensitivities lie, and ways in which these uncertainties can be interpreted and accommodated in the analysis of the results. The next section describes the primary outputs of the life-table models for mortality and life expectancy. This section is then followed by a description of a separate method for modelling impacts of $PM_{2.5}$ on childhood asthma. Finally, a summary of the methods is provided before the results of the modelling are presented in the next chapter.

7.2 Context

Quantitative health impact assessments involve estimating future rates of mortality and morbidity under different intervention scenarios compared to what is predicted without such interventions. A commonly used approach to the assessment of changes in population mortality due to changes in the environment are life-table models (Miller and Hurley 2003). Lifetables can be used to model patterns of death and survival over time in a population based on changes in age-specific death rates resulting from changes in risk factors (e.g. air pollution). The tables are broken down by sex and mid-year population estimates with recent rates of mortality used in projections of years of life loss (YLL) or gained (YLG), and changes in life expectancy.

The effects on life expectancy and total life-years gained (or lost) can then be calculated and combined with economic or specific quality of life factors to estimate costs and benefits of the changes, as well as, to begin to understand the potential social and societal impacts of an intervention. This type of quantification of health impact has been used to assess air pollution-related health impacts at national scales (e.g., COMEAP, 2010) as well as to assess building level changes in air pollution (e.g., Hamilton et al., 2015; Milner et al., 2015).

7.3 Model description

In the work presented here, life-table models were used to quantify the potential impacts on mortality arising from reductions in indoor $PM_{2.5}$ concentrations through the use of portable air purifiers in homes.

Changes in mortality and life-expectancy were estimated based upon the life table formulae from Miller and Hurley (Miller & Hurley, 2003; Miller, 2010). The model was implemented with the open source statistical software R (R Core Team, 2018). A schematic diagram of the model inputs, structure and flow is presented in Figure 7-1. In this figure, the health model is broken into four main categories: environment, health, exposure and impact. Inputs into the environment group include the starting, or baseline, concentration of $PM_{2.5}$ in residences and the concentration after intervention with PAPs. Uncertainties lie within the model of the efficiency of PAPs to reduce $PM_{2.5}$, and the starting concentration. The health category includes the whole

U.K. population and its mortality rates. An additional model uncertainty is the relative risk (RR) associated with changes in $PM_{2.5}$ exposure, shown between the environment and the impact on mortality. The same underlying mortality rates were assumed to apply in all future years, and birth rates were held the same as those in the starting year (2019).

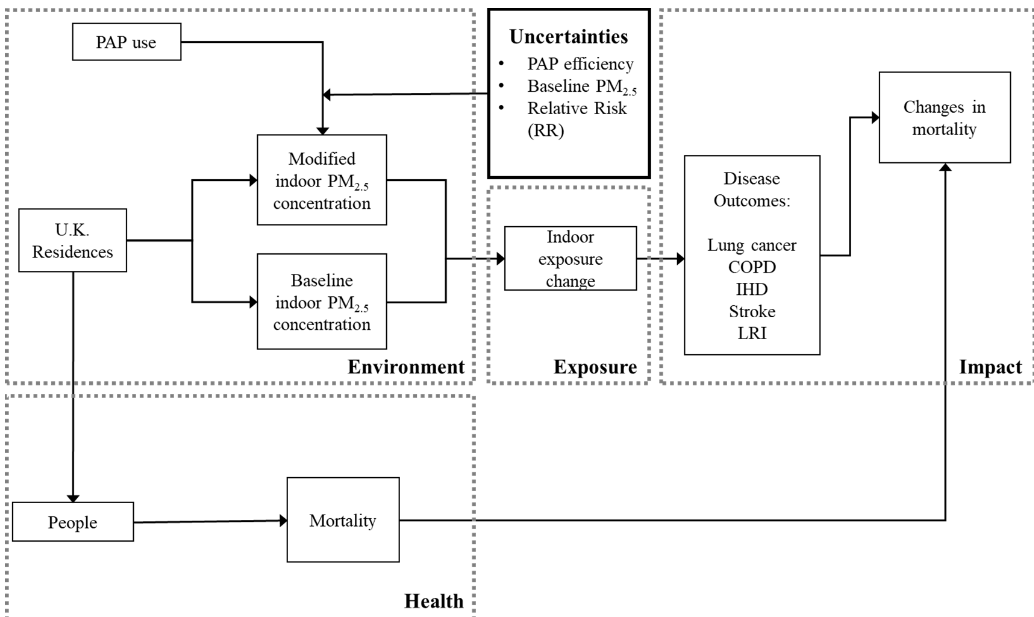

Figure 7-1 Health impact of portable home air purifier use - conceptual framework for life-table calculations

The following are the life-table formulae derived by Miller and Hurley (Miller & Hurley, 2003; Miller, 2010) that were used in the work presented here:

Given a table of age-specific hazard rates h_i, the probability of survival from the i^{th} *birthday* to the next, in one year age groups ($i+1$) is estimated by,

$$s_i = \frac{(2 - h_i)}{(2 + h_i)}$$

Cumulative survival from birth to each birthday ($k + 1$) is calculated as,

$$ {}_0s_{k+1} = \prod_{i=0}^{k} s_i = \prod_{i=0}^{k} s_i \; \frac{(2-h_i)}{(2+h_i)} $$

Life expectancy *E(L)* in life-years can be found from,

$$ E(L) = \sum_{j=0}^{A} 0.5 \; x \; ({}_0S_j + {}_0S_{j+1}) $$

Where ${}_0S_0 = 1.0$ and A is the oldest age achieved in the population so that ${}_0S_{A+1} = 0$

A model that incorporates the effects of the use of PAPs on all members of a population (not just those in the first birth cohort as the formula above) can be denoted with $_0S_a$. This is the part of the original population that survives to the a[th] birthday. An estimate of the remaining expected life given an achieved age *a*, is given by:

$$ E(L \mid a) = \frac{1}{{}_0S_a} \{ \textstyle\sum_j^A 0.5 \text{ x}({}_0S_j + {}_0S_{j+1} \} $$

If ${}_aS_k$ is the proportion of the population achieving age *a* who then survive to their k^{th} birthday, ${}_aS_k = {}_0S_k / {}_0S_a$ and the above can be written,

$$ E(L \mid a) = \{ \textstyle\sum_j^A 0.5 \text{ x}({}_0S_j + {}_0S_{j+1} \} $$

The final output then is the change in the proportion of the population that will survive beyond their predicted life expectancy given the change in $PM_{2.5}$ exposure arising from the use of PAPs.

7.4 Model parameterisation

The life-table model was used to determine the benefit from the reduction of indoor $PM_{2.5}$ in residences in the UK from the use of portable air purifiers. The model was parameterised using population and age-specific disease and mortality data for 2019 from the Office for National Statistics (ONS, 2019). 2019 estimated mid-year resident population in the UK was 66,796,807 (32,978,229 males: 33,818,807 females). 2018 deaths in the UK were 616,014 (304,373 males, 311,641 females).

Mortality rates for causes listed in the Global Burden of Disease (GBD) found to be associated with $PM_{2.5}$ were included in the model; all-cause, lung cancer, chronic obstructive pulmonary disease (COPD), lower respiratory infection (LRI), stroke and ischemic heart disease (IHD). Age-specific all-cause and disease specific mortality rates were taken from the 2019 GBD study (data described in Murray et al., 2020).

The mean indoor pre-intervention $PM_{2.5}$ concentration in UK homes of 11.4 $\mu g/m^3$ used in the model was from a monitoring study in the UK by Lai et al. (2004). The percentage reduction of $PM_{2.5}$ used in the model was 52%. This percentage was the mean of the means of measured efficiencies of PAPs found in the literature (Table 7-3). The percentage reduction results from Lai et al. (2004) were in line with those found in the monitoring work done as part of this thesis (which can also be found in (Cooper et al., 2021a). A percentage reduction was used rather than an absolute reduction because it better represents the actual operation of PAPs in homes, allowed for sensitivity analysis of PAP efficiencies and provides estimates of impacts that are sensitive to pre-intervention $PM_{2.5}$ concentrations. The baseline concentration (11.4 $\mu g/m^3$) as reported in Lai et al. (2004) is much higher than that measured in the London monitoring study (a mean of 6.6 $\mu g/m^3$). However, the London buildings were not representative of the general housing stock of the UK, as they were recently built, low-energy buildings with EPC ratings of B (the average UK EPC rating is D). Therefore, the Lai et al. (2004) baseline concentration was chosen as a more likely representation of existing average housing conditions in the UK

The relative risks for each cause of death (and all-cause) were from the GBD (WHO, 2019). The upper and lower confidence intervals of the RRs were calculated which allowed for the testing of impact across the range of potential risk (which will be further discussed in the next section).

Four scenarios were defined to assess the changes in mortality under different conditions, a summary of these can be found in Table 7-1. The central scenario ('All at Home') was based on measured data from 18 London flats that participated in the Quasimodo study. The mean total hours of PAP use by all participants in the Quasimodo study was 15.6 hours/day (Cooper et al., 2021a). 'All at Home' examined the impacts on the current UK population, including all ages from birth upwards, for the 97-year modelled study period. Further scenarios were used to examine differences in impact that could result from different periods of daily and lifetime PAP use. Two scenarios, 'All Sleep' and '65+ Sleep', modelled the use of PAPs only during sleeping hours. Night-time use assumed that the occupants were in the same room as the PAP the entire time, thereby reducing some uncertainty from the model. The '65+ scenarios ('65+ at Home' and '65+ Sleep') selected only those in the population 65 and older to reflect evidence from another study that found the health benefits of PAPs were highest, relative to the costs, for this age group (Fisk & Chan, 2017b).

Table 7-1 Summary of different modelled scenarios, including baseline $PM_{2.5}$ concentration, PAP use and duration of intervention

	All at Home (central scenario)	**All Sleep**	**65+ Sleep**	**65+ at Home**
$PM_{2.5}$ concentration indoors (µg/m^3) [a]	11.4	11.4	11.4	11.4
PAP use (hours/day)	15.6 [b]	8	8	21.6
Duration of use (years)	97	97	33	33
Starting age	birth	birth	≥65y.o.	≥65y.o.

[a] Monitored mean indoor $PM_{2.5}$ concentration from Lai et al. (2004)

[b] Monitored mean daily PAP use from Cooper et al. (2021a)

Findings from COMEAP (2010) showed that the use of a lag between the intervention that reduces $PM_{2.5}$ concentrations and changes in health outcomes (i.e., cessation lag) made relatively little difference to the lifetable results over the long-term. Therefore, the model used in the work described here does not include a cessation lag.

7.5 Uncertainty analysis

Three further analyses were run to assess key uncertainties in the model, and to gain a better understanding of the sensitivity of the model to parametric changes. A summary of these tests is shown in Table 7-2.

Table 7-2 Summary of model inputs analysed for uncertainty and sensitivity

	PAP Efficiency	Relative Risk	Pre-intervention indoor $PM_{2.5}$ concentration (μg/m³)
Central Scenario	Mean	Mean	11.4 [d]
Test 1: PAP efficiency distribution	Mean, Min., Max.[a]	Mean	11.4 [d]
Test 2: Coefficient of risk distribution	Mean	Mean, Min., Max.[b]	11.4 [d]
Test 3: Pre-intervention indoor $PM_{2.5}$ concentration	Mean	Mean	6.6[c] and 18.8[de]

[a] See Table 7-3 for a summary of PAP efficiencies from the literature
[b] Lower and upper confidence bounds, and means, of relative risk from (WHO, 2019)
[c] Measured mean in 18 East London flats (Cooper et al., 2021a)
[d] Lai et al. (2004)
[e] Shrubsole et al. (2012)

7.5.1 Test 1: PAP efficiency

The first analysis (Test 1) tested the effect that varying the efficiency of the PAP had on the modelled impacts. The measured range of $PM_{2.5}$ reduction efficiencies of PAPs in real-world conditions reported in the literature (Table 7-3) were used in all four modelled scenarios. These efficiencies ranged from a low of a 29% reduction in indoor $PM_{2.5}$ to a high of 82.7%. Although the range was relatively large, the majority of studies, and the results from the Quasimodo study, clustered around a 50% reduction.

Table 7-3 Summary of studies on the effects of portable air purifier use on the reduction on $PM_{2.5}$ in residences

First author (publication year) country	**Study design, sample size, characteristics**	**Study duration**	**Indoor $PM_{2.5}$ concentration (µg/m^3); mean or median, SD during intervention and control; % reduction**	**% Reduction in $PM_{2.5}$**
Allen (2011) Canada	Randomised crossover trial, 25 homes, non-smokers	7 days	Mean ±SD (p-value): control: 11.2 ± 6.1 (<0.01) Intervention: 4.6 ± 2.6 (<0.01) %reduction: 58.9	58.9
Barn et al. (2008) Canada	Randomised crossover trial, 32 homes, non-smokers	2 days	Mean ±SD (p-value): control: 6.7 ± 20.7 (<0.01) Intervention: 4.2 ± 7.3 (<0.01) %reduction: 37.3	37.3
Barn et al. (2018) Mongolia	Randomised controlled trial, 512 pregnant adults, non-smokers	7 days	GM (95%CI): control: 24.5 (22.2, 27.0) Intervention: 17.3 (15.8, 18.8) %reduction 29.0	29.0
Brauner et al. (2008) Denmark	Randomised crossover trial, 21 homes, non-smokers	2 days	GM (95%CI): control: 12.6 (11.2, 14.1) Intervention: 4.6 (3.5,6) %reduction 63.5	63.5
Brehmer et al. (2019) China	Randomised crossover trial, 43 children	14 days	Mean ±SD (p-value): control: 34 ± 17 (<0.01) Intervention: 15 ± 9.6 (<0.01) %reduction: 63.5	63.5
Brehmer et al. (2019) China	Randomised crossover trial, 43 children	14 days	Median (IQR), (p-value): Control 30 (19) Intervention: 13 (15) (<0.05) %reduction: 55.9	55.9
Butz (2011) USA	Randomised 3-arm controlled trial, 126 children with asthma with smoker	7 days	Mean ±SD (p-value): control: 38.9 ± 25.0 (<0.01) Intervention: 17.9 ± 15.2 (<0.01) %reduction: 54.0	54.0
Cheng et al. (2016) USA	Randomised controlled trial, 8 homes, non-smokers	12 weeks	5- min aggregated median/mean (p-value): control: 5.2/6.1 Intervention: 2.6/4.0 (<0.001) %reduction: 37.0	37.0

Cooper et al. (2021a) UK	Randomised crossover trial, 18 households	6 months	Median: 6.6	45.0
Cox et al. (2018) USA	Randomised controlled crossover trial, 43 homes near major road	4 weeks	Median (p-value): control baseline: 9.6 Control filter: 8.2 Intervention baseline: 7.6 Intervention filter: 3.4, (0.0125) %reduction: 58.5	58.5
Eggleston et al. (2005) USA	Randomised controlled trial, 97 children with asthma	72 hours	Median (IQR), (p-value): Control 30 (20-45) Intervention: 24 (10-43) (<0.001) %reduction: 36.8	36.8
Huang et al. (2020) USA	Randomised crossover trial, 6 homes, non-smokers	21 days	Mean ±SD (p-value): control: 14.2 ± 20.9 (<0.01) Intervention: 8.5 ± 8.3 (<0.01) %reduction: 41.6	41.6
James et al. (2019) USA	Randomised crossover trial, 37 homes near major road	2 days	Median (range), (p-value): Control baseline: 10.4 (0.6-53.2) control filter: 7.8 (<LOD-37.9) intervention baseline: 12.0 (0.3-80.9) intervention filter: 4.5 (1.1-18.0) (<0.0125) %reduction 62.5	62.5
Kajbafzadeh et al. (2015) Canada	Randomised controlled trial, 44 homes, non-smokers	7 days	Median/mean ±SD: control: 7.5/7.1 ± 6.1 intervention: 3.7/4.3 ± 2.6 %reduction: 40.0	40.0
Karottki (2013) Denmark	Randomised controlled trial, 27 homes, non-smokers	14 days	Median (5th-95th percentile): Living room: control: 8 (3.4, 20.7) intervention: 4.3 (0.2, 12.2) Bedroom control: 7.6 (1.4, 19.2) intervention: 3.7 (1, 14) %reduction: Living room:46.3 Bedroom: 51.3	51.3
Liu et al. (2018b) China	Randomised crossover trial, 20 homes, non-smokers	14 days	Mean ±SD: control: 58.24 ± 52.74 Intervention: 37.99 ± 45.89 %reduction: 34.8	34.8
Maestas et al. (2019) USA	Randomised crossover trial, 40 homes, non-smokers	3 days	Mean ±SD, (range) (p-value): control: 17.5 ± 16.9 (4.1-117.5) LE: 8.4 ± 5.4 (1.3-39.5) HE: 7.0 ± 4.5 (1.1-30.8) (<0.001) %reduction: LE: 52.0 HE: 60.0	Low efficiency: 52.0 High Efficiency: 60.0

McNamara et al. (2017) USA	Randomised controlled trial, 48 homes, wood stoves	5 months	Medina (range): control baseline: 19.8 (6.0, 101.9) Control filter: 22.0 (2.4, 163.2) intervention baseline: 15.7 (6.1, 63.1) intervention filter: 5.7 (0.7, 65.6) %reduction: 66.0	66.0
Morishita et al. (2018) USA	Randomised crossover trial, 40 homes, non-smokers	3 days	Median/mean ±SD: control: 13.1/17.5 ± 13 LE: 7.8/8.4 ± 3.9 HE: 6.0/7.1 ± 3.5 %reduction: LE: 52.0 HE:60.0	Low efficiency: 52.0 High Efficiency: 60.0
Park et al. (2017) USA	Randomised crossover trial, 16 homes	12 weeks	Mean ± SEM (p-value): Baseline: 7.42 ± 1.42 week 6 intervention: 4.76 ± 0.65 week 12 intervention: 4.28 ± 0.81 (p<0.001) %reduction: 43.0	43.0
Rice et al. (2018) USA	Unmasked trial, 82 participants, smoke in home	5 weeks	Median (IQR), (p-value): pre-intervention: 31 (17, 63) post-intervention: 17 (10,35), (<0.001) % reduction: 45.0	45.0
Shao et al. (2017) China	Randomised crossover trial. 20 homes, non-smokers	14 days	Mean ± SD (p-value): 10-day average: control: 60 ± 45 intervention: 24 ± 15 (<0.01) %reduction: 10-day average: 60.0	60.0
Spilak et al. (2014) Denmark	Randomised crossover trial, 28 homes	14 days	Mean (95% CI): control bedroom: 8.33 (6.72-9.93) control living: 8.32 (6.95-9.69) intervention bedroom: 4.74 (3.53-6.68) intervention living: 4.48 (3.35-6.06) %reduction: 54.5	54.5
Ward et al. (2017) USA	Randomised controlled crossover trial, 98 homes with wood stoves	5 months (winter)	Median (range): Control baseline:16.1 (3.9, 508.2) control filter: 16.9 (2.4, 163.2) intervention baseline: 17.1 (6.1, 163.1) intervention filter: 6.5 (0.7, 65.6) %reduction: 68.0	68.0
Weichenthal et al. (2013) Canada	Randomised crossover trial. 37 participants	7 days	Median/mean ± SD: Control: 42.5/61.0 ± 64 intervention 22.0/30.0 ± 30 %reduction: 50.8	50.8

Kearney et al. (2014) Canada	Randomised crossover trial, 31 homes	3 days	Gravimetric median (min-max): Control 3.87 (0.37-30.19) intervention: 1.92 (0.35-11.28) %reduction: 52.0	52.0
Zhan et al. (2018) China	Randomised crossover trial, 6 participants	4 weeks	Mean: control: 49.0 intervention: 8.47 %reduction: 82.7	82.7

7.5.2 Test 2: Upper and lower 95% confidence interval limits of RR

Recognising that the exposure-response function per change in $PM_{2.5}$ could introduce uncertainty into the model, the second part of the testing (Test 2) examined the effect of using the upper and lower 95% confidence intervals from the distribution of the RRs derived from the 2019 Global Burden of Disease. This test was in line with the recommendations for sensitivity analysis made by COMEAP (2010).

7.5.3 Test 3: mean pre-intervention indoor $PM_{2.5}$ concentration

Test 3 investigated the effect of the mean starting (i.e., pre-intervention) concentration of indoor $PM_{2.5}$ on changes in mortality estimates. The model used percentage reduction of $PM_{2.5}$ to measure efficiencies of PAPs, rather than absolute reductions, as described in the methods. Therefore, effects on mortality were expected to be approximately linearly proportional to the change in starting concentration. That is, a starting concentration of 9.4 $\mu g/m^3$ would generate roughly half the impact that would be seen with a starting concentration of 18.8 $\mu g/m^3$, all things being otherwise equal. Given this assumption, modelling different starting concentrations provided a reliable and simple means of testing the functionality of the model whilst also providing useful metrics to compare mortality across a range of IAQ conditions likely to be present in real dwellings.

Each scenario was modelled with three different pre-intervention indoor $PM_{2.5}$ concentrations. In addition to the concentration of 11.4 $\mu g/m^3$ used in the main analysis, a higher concentration of 18.8 $\mu g/m^3$ was used, based on a modelling study of London housing, and an outdoor $PM_{2.5}$ concentration of 9.0 $\mu g/m^3$ (Shrubsole et al., 2012). The lowest pre-intervention concentration of 6.6 $\mu g/m^3$ was the mean concentration measured in London flats in the Quasimodo study (Cooper et al., 2021a).

One explanation for this low indoor concentration is that these flats were recently constructed, well-sealed and energy-efficient, and some were equipped with MVHR (as described in chapter 3). A summary of modelled and measured indoor $PM_{2.5}$ can be found in Table 7-4. Additionally, during the monitoring period, the outdoor $PM_{2.5}$ concentrations measured at the buildings were often lower than annual London roadside means (Figure 4-1) which may have influenced indoor levels.

Table 7-4 Summary of findings reported from modelling and monitoring studies of indoor $PM_{2.5}$ in UK domestic buildings.

First author (publication year)	**Study design, characteristics**	**Indoor** $PM_{2.5}$ **concentration (µg/m³)**
Shrubsole et al. (2012)	Modelled with CONTAM, non-smoking	AM[1]: 28.4 (present day outdoor $PM_{2.5}$ concentrations) AM[1]: 18.8 (2050 outdoor $PM_{2.5}$ projections) [*]
Hamilton et al. (2015)	CONTAM, standardised indoor in England	AM[1]: 17.8 (SD: 0.7)
Lai et al. (2004)	Monitoring in Oxford, UK	GM[2]: 11.4 GSD[3]: 2.4
Cooper et al. (2021a)	Monitoring in London, UK	AM[1]: 6.6

[1] AM : Arithmetic mean
[2] GM: Geometric mean
[3] GSD: Geometric standard deviation
[*] The 2050 projections for outdoor $PM_{2.5}$ were used to reflect that most of the modelled period falls beyond this date.

7.6 Model outputs

The life-table models described here provided estimates of the differences in mortality between a mean pre-intervention concentration of $PM_{2.5}$ indoors in homes in the UK of 11.4 µg/m³, against alternative scenarios that utilised PAPs to reduce indoor levels. The model calculated changes in mortality for all combinations of ages (in 5-year increments), by gender, and calendar year. Changes to life expectancy at birth were estimated based upon the calculated YLG divided across the whole population. Permanent changes in hazards (i.e., reductions in indoor $PM_{2.5}$ exposure) are expected to confer benefits every year into the future. However, it is typical in health models to discontinue the accumulation of benefit at some point due to greater and greater uncertainties about future conditions. In the work presented here, that point is 97 years from the start (2019), at a time that almost all in the first birth cohort have reached zero survival.

7.7 Modelling impact of $PM_{2.5}$ on childhood asthma

In addition to the population wide lifetable mortality modelling, additional analysis of childhood asthma morbidity was undertaken using a simple arithmetic model described below (Eq. 1). The focus of this analysis was childhood asthma due to its relatively high prevalence in the UK, and its known association with $PM_{2.5}$ (Gehring et al., 2010). The model assumed the persistence of symptoms until approximately age 14 years because asthma in children most often improves with time and diminishes with reductions in exposure. The relationship between exposure and health outcomes applied was based primarily upon epidemiological studies of outdoor concentrations due to the predominance of studies based in these exposures (Gehring et al., 2010; Pope, 2002; Qiu et al., 2018). The location of the PAP was assumed to be in the bedroom of the affected child, and median daily time spent in bedrooms was estimated to be 11 hours and 31 minutes, based upon available literature on activity and sleep patterns of children (Blair et al., 2012; Jones & Ball, 2014). Any disease or health condition can be assigned a measure of impact, often called a harm class which is assigned by the Housing Health and Safety Rating System (Office of the Deputy Prime

Minister, 2006), which can then be used in models to evaluate population-level effects weighted by the multiplication of the prevalence of the disease by the harm class. Asthma prevalence in the UK, including the assigned harm class by severity of symptoms or outcomes, exposure-response functions, and quality adjusted life years (QALYs) by harm class are summarised in Table 7-5. QALYs are uses to report results in the model for the case of childhood asthma because it is infrequently fatal, often resolves after childhood, but has serious impacts on the quality of life of children including time in hospital, at home, and away from school.

Table 7-5 Asthma morbidity outcomes (top), exposure-response functions (middle), and QALY weights by harm class (bottom)

Health outcome prevalence by harm class			
Harm class	**Outcomes**	**Prevalence (children)**	**Source**
I	Mortality	(Not included)	-
II	Hospital admissions, respiratory disease	0.001	(HHSRS* 2003)
III	Asthma, respiratory disease	0.016	As above
IV	Rhinitis, cough, wheeze	0.093	As above

Exposure-response functions by harm class			
Harm class	**Outcomes**	**Exposure-response**	**Source**
I	(Not included)	-	-
II	Hospital admissions, respiratory disease	1.17	(Qui et al., 2018)
III	Asthma, respiratory disease	1.25	(Gehring et al., 2010)
IV	Rhinitis, cough, wheeze	1.18	(Gehring et al., 2010)

QALY weights by harm class			
Harm class	**Outcomes**	**QALY weight**	**Source**
I	(Not included)	-	-
II	Hospital admissions, respiratory disease	0.75	(Hamilton et al., 2015)
III	Asthma, respiratory disease	0.9	As above
IV	Rhinitis, cough, wheeze	0.9	As above

Annual health benefits of air purifiers to reduce the number of children with respiratory symptoms compared to those without air purifiers, Z, is calculated from input data (Table 7-5) using Eq. (1):

$$\sum Z_j = N\,x\,\left(\left(1 - S_j\right)x\,RR_j^{C_i/\delta_{er}}\right)xT_e) - N\,x\,\left(\left(1 - S_j\right)x\,RR_j^{C_p/\delta_{er}}\right)xT_e) \qquad (1)$$

Where, Subscript j refers to harm class (II, III, or IV); N is the number of children in the affected population; S is the harm class severity weight; RR is the relative risk; C_i is the initial concentration of $PM_{2.5}$; Cp is the post-intervention concentration of $PM_{2.5}$; δ_{er} is the rate of change in exposure-response function (3.2 $\mu g/m^3$); and, T_e is the length of exposure (time spent in bedroom).

7.8 Summary

The methods of modelling future changes in mortality described in this chapter allow for great flexibility in the range and type of intervention for comparisons. The scenarios chosen in this thesis do not, and cannot, represent all future potential changes even within the single intervention type of PAP use. However, lifetable models provide a basis from which comparisons of different future predictions can be made, and whose results can be summarised in different ways (e.g., converted into QALYs) depending on how the results will be used. For example, in the prioritisation of policy changes or in the assessment of economic impacts.

The limitations of health models include the nearly infinite unknowable futures, but they can be useful tools, when appropriately bounded by the acknowledgement of assumptions, sensitivities and uncertainties, in estimating impacts and crafting policy.

Chapter 8 Results – Health Impact Assessment

8.1 Outline

This chapter presents results from the health modelling undertaken to estimate the impact of PAP use on mortality, and childhood asthma. The chapter is divided into the following sections, the quantification of mortality impact, uncertainty analyses, impacts on childhood asthma, and a summary of the findings.

Results from the monitoring in London (Quasimodo) that informed the parameterisation and testing of the model are described in detail in Cooper et al. (2021a). The estimated impact on mortality and life-expectancy is reported for each modelled scenario in the following section. This is followed by the findings of sensitivity and uncertainty analyses of the model. Finally, the estimated additional benefits of childhood asthma amelioration are presented.

8.2 Quantification of mortality impact

The central scenario, 'All at Home', modelled the use of PAPs by the whole UK population for 15.6 hours/day, the average daily duration of PAP use reported by Cooper et al. (2021a). This scenario increased the number of years of life (YLG) in the UK by roughly 23 million YLG over the modelled period (97 years beginning in 2019). This YLG translates to an additional 138 and 120 days of life expectancy for males and females, respectively. The 'All Sleep' scenario led to over 12 million YLG and over two months of added life expectancy. On the other hand, the 'All >65 and '>65 Sleep' scenarios added only about 25% and 10% of the YLG as the central scenario (5.8 and 2.2 million YLG), respectively. These findings are approximately representative of the portion of the population that is elderly, and the shorter duration of the intervention compared to the central scenario. A summary of the findings for all scenarios can be found in Table 8-1.

Table 8-1 Summary of life-table model results for the baseline case (mean RRs, mean PAP efficiency, starting $PM_{2.5}$ concentration 11.4 μg/m^3)

Outcome	Population	All at Home (central scenario)	All Sleep	>65 Sleep	>65 at Home
Average years of life gained (YLG)	Male	12,427,646	6,385,418	1,150,070	3,023,585
	Female	11,140,862	5,725,708	1,066,704	2,801,626
	Total	23,568,509	12,111,126	2,216,774	5,825,211
Average days gained	Male	138	71	13	34
	female	120	62	12	30

Irrespective of the scenario, the distribution of deaths amongst the causes (e.g., lung cancer, stroke) remains unchanged, differing only slightly between males and females, but remaining proportional to the differences in the disease-specific mortality rates between the sexes within the UK population. The contribution of each disease to total deaths attributable to $PM_{2.5}$ is presented in Table 8-2.

Table 8-2 Distribution of disease-specific $PM_{2.5}$ attributable deaths in the UK

Cause of death	Percentage of deaths attributable to $PM_{2.5}$ (Males)	Percentage of deaths attributable to $PM_{2.5}$ (Females)
Lung cancer	3%	1%
LRI	28%	27%
COPD	7%	9%
IHD	32%	28%
Stroke	29%	35%
Total $PM_{2.5}$ attributable deaths	100%	100%

8.3 Sensitivity and uncertainty analyses

Several tests were run to assess the sensitivity of the parameters defined in the scenarios. In the first test the $PM_{2.5}$ reduction efficiency of the PAPs was tested, all other scenario parameters remained unchanged from the baseline model. Two reduction efficiencies were modelled, a low efficiency PAP (29%) and a high efficiency PAP (82.7%). The effect on mortality from the low efficiency PAP was approximately 12 million YLG for the baseline scenario, compared to a maximum of more than 34 million YLG for the high efficiency PAP. These model results translate to average days gained in life expectancy in the low efficiency situation of 75 days for males and 65 days for females. In contrast, the high efficiency PAPs would add 201 days for males and 175 days for females. The test suggests that the relationship between reduction efficiency, or absolute reduction in $PM_{2.5}$ was nearly, but not quite, linear. In turn this suggests that the pre-intervention concentration is a critical factor in the selection of how to prioritise PAP use. A summary of Test 1 results for all scenarios is shown in Table 8-3 and Table 8-4.

Table 8-3 Test 1, sensitivity to a reduction in air purifier efficiency modelled for all scenarios using the baseline starting concentration and RRs with a low PAP reduction efficiency of 29%

Test 1: Low PAP efficiency (29%), Mean RRs, all-cause mortality

Outcome	Population	All at Home	All Sleep	>65 Sleep	>65 at Home
Average years of life gained (YLG)	male	6,732,391	3,340,993	601,379	1,778,332
	female	6,036,729	2,996,454	557,911	1,651,856
	Total	12,769,120	6,337,447	1,159,290	3,430,187
Average days gained	male	75	37	7	20
	female	65	32	6	18

Table 8-4 Test 1, sensitivity to an increase in air purifier efficiency modelled for all scenarios using the baseline starting concentration and RRs with a high PAP reduction efficiency of 82.7%

Test 1: High PAP efficiency (82.7%), Mean RRs, all-cause mortality

Outcome	Population	All at Home	All Sleep	>65 Sleep	>65 at Home
Average years of life gained (YLG)	male	18,122,902	9,429,842	1,698,762	4,268,839
	female	16,244,995	8,454,962	1,575,496	3,951,396
	Total	34,367,897	17,884,804	3,274,258	8,220,234
Average days gained	male	201	104	19	47
	female	175	91	17	43

Due to the, often large, differences between the upper and lower confidence limits of the GBD RRs, the RR used in the model has a substantial impact on mortality effects (Table 8-5). In the case of central scenario 'All at Home', the difference between the lower and upper limits of the RR for all-cause mortality is more than 26 million YLG, twice again the results of the finding from the main analysis (23 million). This translates to a difference in average additional life expectancy for males in the UK of 58 days vs. 211 days for the lower and upper limits, respectively. While for females the lower limit of the 95% CI of RRs adds 51 days to the average life expectancy and more than 183 days for the upper limit.

Table 8-5 Test 2: effect of changes in relative risks using the upper and lower 95% CIs from the GBD.

Scenario	RR (95% CI upper and lower)	LYG male	LYG female	LYG total pop.
All at Home	lower	5,199,315	4,766,868	9,966,183
	mean	12,427,646	11,140,862.2	23,568,509
	upper	19,101,247	17,011,072	36,112,318.9
All Sleep	lower	3,488,054	3,215,593	6,703,646
	mean	6,385,418	5,725,708	12,111,126
	upper	9,499,523	8,466,178	17,965,700
>65 Sleep	lower	634,899	604,546	1,239,444
	mean	1,150,070	1,066,704	2,216,774
	upper	1,702,346	1,570,852	3,273,198
>65 at Home	lower	1,079,418	1,010,350	2,089,769
	mean	3,023,585	2,801,626	5,825,211
	upper	4,755,453	4,381,854	9,137,307

The final test of the model generated results based on different starting (pre-intervention) concentrations of indoor $PM_{2.5}$. The lowest starting concentration modelled was 6.6 μg/m^3 and the highest was 18.8 μg/m^3. As noted in the methodology section, the model used percentage reductions of $PM_{2.5}$, rather than absolute reductions. Therefore, effects on mortality were as expected, approximately linearly proportional to the change in starting concentration. The YLG for the pre-intervention concentration of 6.6 μg/m^3 was just under 11 million, whilst for 18.8 μg/m^3 the YLG was almost 37 million.

Table 8-6 Results from changes to pre-intervention $PM_{2.5}$ concentrations, 6.6 (top) 18.8 (bottom)

Baseline $PM_{2.5}$ concentration 6.6 µg/m3

Outcome	Population	All at Home	All Sleep	>65 Sleep	>65 at Home
Average years of life gained (YLG)	male	5,733,909	3,226,968	582,763	1,292,599
	female	5,111,198	2,883,609	538,704	1,188,735
	Total	10,845,107	6,110,577	1,121,467	2,481,334
Average days gained	male	63	36	6	14
	female	55	31	6	13

Baseline $PM_{2.5}$ concentration 18.8 µg/m3

Outcome	Population	All at Home	All Sleep	>65 Sleep	>65 at Home
Average years of life gained (YLG)	male	19,350,912	9,677,814	1,737,871	4,880,103
	female	17,416,358	8,723,828	1,620,836	4,539,975
	Total	36,767,270	18,401,643	,358,707	9,420,078
Average days gained	male	214	107	19	54
	female	188	94	17	49

8.4 Impacts on childhood asthma

For the estimation of the impact of $PM_{2.5}$ reduction at home on childhood asthma, the same pre-intervention $PM_{2.5}$ concentration and mean PAP efficiency used in the central scenario of the lifetable models (11.4 µg/m^3 and 52% respectively) was used to calculate the impact on life quality. QALYs were used to communicate impact because mortality is relatively low for asthma in children, but morbidity effects can be significant. The number of QALYs gained by using appropriately sized and well-functioning air purifiers in the bedrooms of children during sleep is estimated to be 1,116 per 10,000 children annually (Table 8-7).

Table 8-7 Health impact calculations by harm class and air purifier use, QALYs calculated per 10,000 children

HIA calculation (per 10,000 children spending 11.5 hours/day in filtered bedroom)			
Impact (QALYs)			
Harm class	*Pre-intervention with PAP*	*Post-intervention with PAP*	*Impact (pre-post QALYs gained)*
II	2,096	1,567	529
III	1,061	702	359
IV	864	636	228
Total	4,021	2,905	**1,116**

Additional information and a further discussion of the results of the impact of PAP use in the bedrooms of children with asthma can be found in Cooper et al. (2021b).

8.5 Summary

The results of the health impact modelling support the hypothesis that the reduction of indoor $PM_{2.5}$ exposure achievable by PAPs would positively impact mortality and increase QALYs associated with childhood asthma morbidity in the UK. The scale of the impact varies depending on a number of factors explored in the models, but the direction of impact remains consistently positive (i.e., beneficial for health). Specific variables, their impacts and implications are discussed in the following paragraphs.

The length of the intervention, meaning either for all hours whilst at home or just during sleep is proportional and perhaps ideally air purifiers could be operating in the whole house at all times of the day. However, expense and user convenience are likely to be important factors in user compliance. For this reason, the use of PAPs during sleep, over the lifetime of the user may be a reasonable level of use for most people.

The impact of relative risk was substantial, but without additional epidemiological evidence, the true risk remains unknown. Providing a range, or distribution of risk, is the current best method for estimating the probabilities of hazards associated with different levels of exposure.

The efficiency of the PAP may be one of the only variables about which users have some control. The most efficient PAP that was modelled (central scenario) provided an additional 126 days of life expectancy to males and 110 extra days for females. The condition that, for many households, cannot easily be controlled is the starting concentration of $PM_{2.5}$. Higher starting levels will always impact mortality rates due to the limitations of the efficacy of PAPs to reduce $PM_{2.5}$.

The implications of the modelling results, the magnitude of the measured reduction in $PM_{2.5}$ concentrations in indoor air, occupants' perceptions of the quality of the air in their homes and the potential impact on their behaviour, will be discussed in the next chapter.

Chapter 9 Discussion

9.1 Outline

This chapter provides a discussion of the results of the work across the entire thesis, the strengths and weaknesses of the study, findings in the context of the wider field of IAQ policy and building design, and an introduction to the implications for future work.

In the first section of this thesis results from a monitoring study completed in 18 flats in London were presented. $PM_{2.5}$ concentrations in these flats were generally low with occasional, and predictable, peaks that exceeded the WHO recommendations. The background indoor $PM_{2.5}$ concentrations were typically reflective of outdoor levels associated with high traffic volumes. The high peaks occurred during times that coincided with cooking activities, in particular the preparation of evening meals. When PAPs were used there were substantial reductions in $PM_{2.5}$ concentrations, both of background levels and during peaks. The mean reduction after 90 minutes of PAP use was 45%.

The qualitative analysis of occupant behaviour and PAP use found that the use of PAPs was not directly associated with poor indoor air quality from $PM_{2.5}$, but rather that occupants used the PAPs more often when the indoor temperatures were high. This result is in line with the observation that occupants found that the temperatures in their homes in the non-heating season were too high, and that they expressed opinions that the PAPs acted as cooling devices (despite the fact that the devices did not have cooling capacity). Although the results of surveys on the effect of PAPs on sleep quality were not entirely convincing, there was some indication that some participants' sleep quality did improve with PAP use.

The results of the health impact modelling clearly demonstrated population level benefits to mortality and life expectancy from the reduction of $PM_{2.5}$ through the use of PAPs in homes. The central scenario increased the number of years of life (YLG) in the UK by roughly 23 million YLG over the modelled period (97 years beginning in 2019). This YLG translates to an additional 138 and 120 days of life expectancy for males and females, respectively. The next section discusses these results in the context of other work in the field.

9.2 The work in the context of the wider field of IAQ

There is very little, if any, published work that does what this thesis has attempted to do. That is to link air quality monitoring data, analysis of occupant behaviour, and health impact assessments due to changes in the built environment. As evidenced by the results of this thesis, methods that link monitoring, multi-domain approaches to behavioural analysis, and health modelling hold promise to better inform design and operation of buildings, and policy change. Direct comparisons between this work and the wider field does provide some challenges, however, results from studies of the different aspects of this thesis can be reviewed separately. The following is a summary of other work that reviewed or analysed similar aspects of the work of this thesis.

The average reduction in indoor $PM_{2.5}$ due to PAPs in the work presented here, a mean of 45% after 90 minutes, is in line with those found in other studies. Spilak et al. (Spilak et al., 2014) reported a reduction in $PM_{2.5}$ of 54.5% (median value) in locations using HEPA filtration in a crossover study in Denmark. An intervention study in the

USA by Park et al. (Park et al., 2017) showed a reduction in $PM_{2.5}$ of 43% when HEPA filtration was used. A modelling study by Fisk and Chan (Fisk & Chan, 2017a) simulated the indoor air for a number of scenarios including using portable air purifiers in homes without forced air systems, which closely resembles the typical conditions in London flats. They found in the modelled results that homes with continuously operating portable air purifiers had a reduction of 45% in $PM_{2.5}$ concentrations. In the work presented here, aggregated, normalised concentrations in the bedrooms, from the internal PAP sensors, showed improvement of air quality when using the device. The median percentage reduction after 30 min was 20%, median percentage reduction after 60 min was 34%, and after 90 min a median reduction of 45% was seen. 30% of the time, after the PAP had run for 30 minutes, concentrations had reduced from their initial concentration by at least 50%, and in 45% of cases after 60 min a reduction of at least 50% was seen. It is also worth noting that the actual running time of the air purifier is often longer than 100 minutes, especially in warmer weather which could lead to larger reductions for longer periods of time. However, there were also many occasions, either due to thermal conditions or perceived air quality, in which residents did not use their PAPs at all.

Most studies reported average percentages of reduction in $PM_{2.5}$, as does this thesis. This is a useful way of presenting the results for the purpose of comparisons, and is useful as applied to modelling (of both PAP effectiveness and potential health impact). In the studies presented in the literature review the absolute pre-intervention concentrations of $PM_{2.5}$ varied from a high of 60 $\mu g/m^3$ in a study from China to a low of 3.9 $\mu g/m^3$ from a study in Canada. The mean baseline concentration of $PM_{2.5}$ was 21.9 $\mu g/m^3$. The absolute concentrations did not correlate with percentage reduction, supporting the use of percentages in presenting and comparing data across studies.

The magnitude of the modelled impacts on mortality presented here are in general agreement with work that achieved reductions in indoor $PM_{2.5}$ in other ways (e.g., mechanical ventilation with filtration, or sealing of the building envelope). One such study estimated the overall impact of energy efficiency upgrades in UK homes and found that for an average $PM_{2.5}$ reduction of 3 $\mu g/m^3$ there was an increase in life expectancy of two to three months (Milner et al., 2015). Another study of improved energy efficiency and ventilation of homes in England found that with a 53% reduction in $PM_{2.5}$ (-4.8 $\mu g/m^3$ mean) the net health impact was an increase of over 2,000 QALYs per 10,000 persons over 50 years of follow-up (Hamilton et al., 2015)

9.3 Interpretation of principal findings

9.3.1 Ventilation vs. indoor pollutant reduction

The results presented in this thesis have important implications for future strategies to improve indoor air quality in the UK, and elsewhere. Proper ventilation for the dilution of indoor pollutants, as well as for occupant comfort and to reduce overheating, is critical but it may not be adequate for the reduction of pollutants of indoor origin (Raw et al., 2004). Additionally, there are recognised shortcomings of the ventilation of UK homes. In a review article by Dimitroulopoulou (2012), the authors reported that ventilation rates in European homes often fall below 0.5 h^{-1} (a common regulatory standard) which can lead to an accumulation of indoor generated air pollutants, and consequently increased pollutant exposure risks. Although there are several ways to achieve the regulatory required air change rate, including continuous mechanical extract, or supply and extract with heat recovery, residences in many places rely primarily, or entirely, upon window openings and uncontrolled ventilation has been common.

In the UK background ventilators (e.g., trickle-ventilators) remain a common approach allowed by Approved Document F (HM Government, 2010) but, as with other types of natural ventilation, they do not have filtration capacity, and leave the indoor air quality heavily dependent upon the quality of the outdoor air. In addition to the reliance upon good outdoor air quality, for events of high indoor pollutant generation (e.g., cooking), ventilation through natural ventilation alone may be inadequate. The results of a BRE (Building Research Establishment) study found that 68% of homes had a whole house ventilation rate below the minimum design value of 0.5 h^{-1} in the winter, and in summer 30% of homes failed to reach this standard (Dimitroulopoulou et al., 2005). Notably, as all the homes in the London monitoring work in this thesis were apartments, in the same BRE study, flats performed even more poorly than other types of homes monitored. The findings of the BRE study, and others, reinforces the need to find ways to better manage IAQ in homes. The findings of this thesis provide evidence for effective and available technologies to reduce $PM_{2.5}$ concentrations indoors irrespective of ventilation type, outdoor concentrations, or indoor generation.

9.3.2 Occupants' perception of IAQ and motivations for PAP use

9.3.2.1 Occupants' opinions on the environmental conditions of their homes

The findings from the participant surveys reported in chapter 6 of this thesis demonstrated that residents were generally dissatisfied with several aspects of their indoor environment. Perhaps most notably, 79% of respondents thought that the air was too still and 63% thought the air was 'stuffy' in the summer, conditions that could be correlated with inadequate ventilation, and therefore with higher levels of indoor air pollutants. Notably, however, measured levels of CO_2 in bedrooms in the summer were relatively low and windows were operated frequently, suggesting that occupants' perception of 'stuffiness' may have been a consequence of higher temperatures rather than perceived air quality. This interpretation is supported by data from the cooler weather of the heating season. In this period high levels of measured CO_2 were measured frequently, especially in bedrooms, indicating a low air exchange rate, but only 27% of occupants reported dissatisfaction with the stuffiness of their homes. Additionally, 69% of the residents reported that it was too hot in the summer, with 68% saying that they were uncomfortable in the summer due to high temperatures.

Even though many of the standards of practice for ventilation are based upon what is *perceived* as acceptable air quality by the vast majority of people (such as ASHRAE Standard 62.1), we know little about whether perception correlates with actual air quality. The evidence presented in this thesis indicates it does not, rather temperature was demonstrated as the most important determinant of air purifier use. The perception of indoor air quality is influenced by many other factors including relative humidity, noise, as well as the actual cleanliness of the air (e.g., Fang, 2004). Historically, bio-effluents from occupants were thought to be the primary pollutant of non-industrial spaces despite recognition that they posed little or no health risks (although we are coming to understand that carbon dioxide may impact cognitive performance at levels commonly found indoors), and dilution via ventilation (often at very high air exchange rates) was seen as the solution (Fanger, 1988; Satish et al., 2012). In more recent times, the focus on reducing greenhouse gas emissions and improving energy efficiency has led to increased airtightness of buildings. The apartment buildings that were monitored in this research reflect this new approach to managing ventilation. Mechanical ventilation with heat recovery (with bypass in the non-heating season) is available for flats located at Site A, but it only includes minimal filtration (ISO coarse 45%), that is not adequate for the removal of $PM_{2.5}$. The achievement of satisfactory indoor air conditions therefore depends upon the occupants to open or close windows, and the cleanliness of the outdoor air. However, if occupants cannot perceive unacceptable $PM_{2.5}$ levels, or if other environmental conditions override their perception, they may not make appropriate decisions in terms of exposure risk reduction. It is evident from the BUS survey results and the monitored use patterns of the PAPs, that occupants are more responsive to changes in thermal conditions than to indoor air pollution.

9.3.2.2 Use of PAPs for "cooling"

There is very little published research on, or references made to, operational behaviour towards air purifiers and the two studies that were found differed substantially in their findings (Pei et al., 2019; Piazza, 2006). The participants in the work presented here reported in conversations that, in large measure, they did not use the PAPs for their intended benefit of reduction in particulate matter, but as cooling fans. This pattern of use could be problematic if in the cooler months, as is typical, window operation declines and indoor cooking activities and candle burning increase (i.e., indoor $PM_{2.5}$ sources increase).

The combination of the residents' perception that the quality of the indoor environment of their homes was more acceptable in the cooler months and that the air purifiers had a "cooling" or "freshening" effect, may have led the residents to use the air purifier less often, or inconsistently, in the heating months, irrespective of the actual air quality, as was demonstrated by the probability of PAP use illustrated in Figure 6-3. This low rate of PAP utilization during the heating season could lead to unacceptable indoor air quality. As people cannot directly perceive $PM_{2.5}$, or may otherwise prioritize thermal comfort, they may not respond appropriately to the actual risk of $PM_{2.5}$ exposure. Given that so many occupants are dissatisfied with the thermal conditions in their homes, and that they reported that the PAP provided "cooling" (likely due to increased air movement caused by the device), it is not surprising that the greatest utilization of the PAPs was seen during the warmest weather.

9.3.3 PAPs effects on mortality

The work presented here provides new insights into the potential effects on mortality that could be achieved with widespread use of PAPs in UK homes. Given what is currently known about the efficiency of PAPs, (see Table 2-2 for a list and descriptions of some of the relevant studies), it is reasonable to expect that when they are operated and maintained properly, reductions in indoor $PM_{2.5}$ of approximately 50% can be achieved. This reduction impacts $PM_{2.5}$-related mortality, and can lead to meaningful increases in life expectancy. For the central scenario, the reduction in $PM_{2.5}$ led to over 23 million YLG, and over 4 months of additional life expectancy for the birth cohort. A study by Milner et al. (2015) reported an increase in life expectancy of two to three months for a 3 $\mu g/m^3$ reduction in $PM_{2.5}$. However, their study only considered improvements in IAQ due to better ventilation, which as previously noted, may not be the best approach to pollution control in many situations. If $PM_{2.5}$ removal efficiency could be increased to the highest reported rate (82.7%) the modelling indicates the mortality effect would be over 34 million YLG, and as much as an additional 200 and 175 days of life expectancy for males and females, respectively. When the upper limits of the RRs were used in the model, the total YLG for ‘All at Home’ rose to over 36 million, illustrating the significance of these exposure-response functions in accurate estimations of effect. Perhaps unsurprisingly, the benefits of PAP use are proportional to several factors including, the pre-intervention concentration, the total years used and duration of daily use.

Surprisingly, in results from the survey data, no correlation was observed between reported health conditions and PAP use, despite many of the participants saying in the baseline interviews that they were concerned about the impact of air pollution on their personal health. Pei et al. (2019) proposed in their work that the substantial difference in the use patterns found in their study and those reported by Piazza (2006) was due to personal health motivations. The findings of this work do not support that supposition, but a larger scale study with unhealthy subjects and healthy controls would be useful in verifying the observations made here.

9.3.4 PAPs effects on childhood asthma

The work of this thesis also produced simple estimates of changes in childhood asthma achievable through the use of PAPs in children's bedrooms. Asthma, especially in children, is of significant concern, and a recent asthma death attribution lawsuit in London (Dyer, 2020) could have implications for policy around $PM_{2.5}$. The potential benefits from the use of PAPs in homes on asthma incidence should be explored. Asthma, therefore, is an important disease for future consideration in health impact assessments, and based on the results from this thesis, there is great potential in targeting interventions for childhood asthma control with PAPs. In addition to asthma, other morbidities associated with $PM_{2.5}$ exposure should be included in future modelling. The total impact to quality of life, as well as the economic implications, due to mortality and morbidity effects of indoor $PM_{2.5}$ are important tools for policymakers to determine the appropriate levels and types of interventions.

9.3.5 Maximising the potential benefits of PAPs

9.3.5.1 Controls

Commercially available home air purifiers do a good job of reducing $PM_{2.5}$ levels from the indoor air (in the rooms in which they are located), but if occupants fail to use them because of a misunderstanding of their utility or a misperception of risk, solutions that take humans out of the loop may be one approach to ensuring that the devices are working as intended and to their full capacity. However, as users generally prefer to have control over the equipment and may disable automation, providing better education and appropriate warning systems could be an alternative or additional strategy (Day & O'Brien, 2017). Integrated sensors, default ON (user must opt-out of PAP use), and integration with ambient air quality data may also be options available to allow the PAPs to function more effectively to reduce $PM_{2.5}$. A study by Huang et al. (2020) supports the use of integrated sensors, and automatic modes. In the study, when people operated their air purifiers on auto-mode, average indoor $PM_{2.5}$ levels reduced by 40% compared to 28% for adjustable-mode. This is an important observation and a solution that obviates the need for monitoring or actions by users who are unlikely to respond directly to poor IAQ.

9.3.5.2 Targeted populations

Previous research has focussed PAP interventions targeting specific populations, such as children or people suffering from cardiac disease, or during specific events, such as wildfires. Results from these studies have shown reductions in indoor $PM_{2.5}$, and some have shown effects on disease indicators (see Chapter 2 for a detailed review of the studies and their findings). Little work has been done assessing the benefits to the general population, under typical ambient $PM_{2.5}$ conditions, for any length of time. However, it is generally accepted that levels of $PM_{2.5}$ that are commonly measured indoors increase the risks of several diseases (i.e., lung cancer, COPD, lower respiratory infections, stroke, ischemic heart disease and childhood asthma). This effect leaves a great many people in the UK, and around the world, vulnerable to the impacts of $PM_{2.5}$ in their homes. Establishing a framework of prioritisation of intervention will be critical in affecting the greatest change. Based on the health impact modelling done in this thesis, the greatest impact in all tests, was to always use the PAPs throughout the occupants' entire lives. However, this represents an enormous economic cost, and a monumental feat of coordination that would tax even the wealthiest and most organised government.

It makes sense then to target populations and places that would most benefit from use of PAPs and that have little access to other means of indoor pollution mitigation. As illustrated in Table 8-6, the higher the pre-intervention concentration of $PM_{2.5}$ the greater the YLG and additional life expectancy. It therefore seems reasonable to begin to prioritise based on the areas with the highest outdoor levels. Although, it is, of course not that simple, as both attenuation by building envelopes and individual behaviours that generate indoor $PM_{2.5}$ will greatly affect the actual levels of $PM_{2.5}$.

Evidence from studies on the effects of PAPs on specific diseases is limited (see section 2.3.3 for a review of these studies), but it remains an area of active research and targeting people with conditions which may be responsive to reductions in $PM_{2.5}$ is another potential strategy to prioritise those most vulnerable to poor IAQ.

Another potential target of policy for prioritisation of interventions with PAPs is through a multidimensional analysis of factors that contribute most significantly to high concentrations of $PM_{2.5}$ indoors. Work has already been published that contributes to our understanding of how socio-economic status influences IAQ

(Ferguson et al., 2020; Ferguson et al., 2021). Although not specifically explored in this thesis, this is an area of study which deserves investigation in future work.

9.4 Strengths, limitations, and recommendations for future work

9.4.1 Strengths of this work

The work of this thesis strengthens the evidence on the effectiveness of PAPs to reduce $PM_{2.5}$ indoors. The six-month duration and continuous nature of the monitoring period (see Table 3-3), across multiple seasons with the associated changes in occupant behaviour (such as window operations) provides a much fuller picture of the seasonal changes in indoor $PM_{2.5}$, changes in occupant behaviour, and opportunities for new interpretations of these behaviours. Additionally, the work done as part of this thesis co-located indoor and outdoor monitors for air pollutants and other physical parameters which is uncommon in similar monitoring studies. The pairing of the data collection allowed for analysis of the contributions of $PM_{2.5}$ by location, and could provide useful information in future analyses and modelling.

Another strength of the work presented here was the real-time monitoring of the PAP use. There is very little information available about how people actually use air purifiers in their homes, and the capturing of these data was instrumental in demonstrating a relationship between PAP use and thermal conditions. This monitoring data, paired with the qualitative evidence collected from participants provided a narrative around motivations for use that will inform better ways of managing PAP use for more effective reductions in $PM_{2.5}$ at the times when those reductions are most meaningful and impactful to occupants.

The lifetable modelling approach that was used in this work has not previously been applied to improvements in air quality from PAPs. However, the modelling method used and the relative risks associated with exposure, are backed by decades of epidemiological studies (e.g., Pope et al., 2020) which reduces the level of uncertainty that can be common and problematic in health assessment models. In addition to the robust epidemiological evidence from years of cohort studies, there are many reports from studies on PAPs used in residences, across dwelling types and locations. The findings have found substantial reductions in indoor $PM_{2.5}$, again increasing confidence in the central scenario.

9.4.2 Limitations and recommendations for future work

9.4.2.1 Financial considerations

A potential factor of low PAP utilization (outside of the crossover period during which the use was directed) was the cost of electricity for operating the device. Many of the participants were receiving some level of housing support based on financial need, and some of them expressed concern about the cost of electricity, which although relatively small at approximately £2-3 per month (or between 3-5% of their monthly bill), was not negligible for some participants. This factor remains a limitation in our understanding of the motivations that could influence occupant behaviour.

9.4.2.2 Equipment

Another limitation of this study was the lack of a sham device. Due to warranty and insurance issues the manufacture would not allow the PAPs to be operated without filters installed, therefore participants were aware when the PAP was off, which may have influenced their opinions about the quality of the air. An additional limitation of the work presented here was that the dedicated (Eltek) indoor air quality monitors were in the living rooms. The air purifiers, which each included an on-board $PM_{2.5}$ sensor, were in the bedrooms. The Eltek monitors use a small fan that switched on and off periodically that was reported in the pre-trial tests as too disruptive to sleep. $PM_{2.5}$ was monitored in the bedrooms using the PAPs' built-in sensors, which were uncalibrated and had limited resolution. However, calibrated sensors collocated with the PAPs were in strong agreement with the levels measured by the air purifiers (R^2 = 0.9, RMSE = 4.5 μg/m^3, MBE = -0.16 μg/m^3). A passive sampling method might be considered in future monitoring studies in bedrooms, and could complement other measurements.

In addition to the many parameters already monitored in this work, information about noise levels within the residences from sources outside the building, within the building but outside the residence, and from within the residence might have provided additional insights into motivations for, or correlations with, PAP use. Although no participant reported sleep disruption due to noise from the PAP, objective observations of noise levels should be considered in future work as previous research on office environments reported an association between satisfaction with the indoor environment and noise (Witterseh et al., 2004).

9.4.2.3 Sample size and pollutant profiles

Additional research should be carried out with a greater number of participants with a focus on specific disease outcomes, and a range of pollutants (e.g., NO_2 and TVOCs). The results presented here remain important due to the demonstrated adverse health impacts of $PM_{2.5}$ and insights on building and city-specific indoor and outdoor dynamics of $PM_{2.5}$. This work considered air purifiers in homes with already low outdoor and indoor $PM_{2.5}$ levels and it is not known that the reported findings on air quality perception and device use hold for areas or homes where $PM_{2.5}$ levels are very high. Additional studies in locations with high ambient $PM_{2.5}$ concentrations should be undertaken to better understand these relationships. Monitoring exposure to a wider range of pollutants should also be included as part of future work, to better understand the levels and types of air pollutants people are subjected to, and if or how they are perceived. That being said, the results presented here are important because $PM_{2.5}$ is a pollutant of significant concern due to its demonstrated negative impact on health.

9.4.2.4 Health impact assessments

Health modelling provides an attractive and useful method of evaluating the impact of interventions on population health. However, the reliability of the results is subject to the accuracy of available sources of information, and the ability to add scientific credibility when those sources are uncertain. For this work, one source of uncertainty was the mean residential indoor $PM_{2.5}$ level in the UK Due to several, poorly characterised, factors, such as occupant behaviours and ventilation type, it is not clear if average concentrations vary widely across the UK housing stock. The mean indoor $PM_{2.5}$ pre-intervention concentrations used in the model were from monitoring by Lai et al. (2004) completed in Oxford, UK The measured mean annual outdoor $PM_{2.5}$ concentration in that study was 6.2 $\mu g/m^3$, lower than the annual UK mean (8.1 $\mu g/m^3$). Therefore, the measured indoor concentration may not be fully representative of the entire UK housing stock. However, modelling of both higher and lower pre-intervention concentrations provided reasonable bounds for potentially variable conditions across the UK

Occupant behaviour is also likely to be one of the most significant factors in both the potential for the generation of, and exposure to, indoor $PM_{2.5}$. Time-activity patterns are poorly characterised and are expected to vary widely by age, location, socio-economic status (SES), etc. Without a better understanding of occupant behaviour, estimations of exposure are likely to be inaccurate. A more comprehensive study with activity diaries, and personal air quality monitoring would add significantly to the information used to assess exposure and to model effects. It is also unlikely that the entire population of the UK (or of any country) could own, and properly operate, PAPs whilst at home for the entirety of their lives. However, the estimation of the impact of use by the whole population for a lifetime is important for establishing metrics against which more feasible and realistic interventions can be compared. Additionally, such work can assist in defining those most susceptible, and most vulnerable, to especially high levels of indoor $PM_{2.5}$ at home.

Although it is widely recognised that there exists $PM_{2.5}$-associated mortality and morbidity, there is debate about the distribution of severity and mechanism of impact (e.g., Bo et al., 2017; Brunekreef et al., 2005). The modelling done for this work was based upon averages, and therefore cannot provide information on specific impacts and associated inequalities. Additionally, whether $PM_{2.5}$ from different sources and, therefore, in different locations, has different impacts on health outcomes is still largely unknown (e.g., Chi et al., 2019; Gotschi et al., 2002). The GBD RR functions represent both indoor and outdoor sources but there is much greater uncertainty about the toxicity of PM from indoor sources. The WHO recommends treating all particles as equally toxic in lieu of evidence to the contrary, so that is what was done in the models used in this thesis. However, this gap in our understanding brings additional uncertainties to the health impact modelling.

With the exception of childhood asthma, this work does not consider morbidity associated with the diseases linked to $PM_{2.5}$ exposure, although this is likely to be considerable as many of these disease (e.g., COPD) can have effects years before death. The work presented here focussed solely on the mortality effects as this provides critical information for assessing risk. However, future work that captures the wider impacts to health should be undertaken.

One important unknown is the distribution of $PM_{2.5}$ concentrations in homes across the UK There has been some modelling work to begin to estimate these levels, but there is little evidence from monitoring studies that would be essential in providing an accurate estimation of the impact of PAPs, specific geographical areas or housing types to target for intervention.

9.4.2.5 Additional considerations

The health impact assessments in this thesis considered long-term exposure to $PM_{2.5}$ on mortality and life expectancy, but there is evidence that short-term exposures are also associated with morbidity and mortality (Di et al., 2017) As evidence for risk curves associated with short-term exposure become available and reliable, additional analysis of the impact of this type of exposure should be investigated.

The work of this thesis focussed on PAP use in bedrooms, but there are other rooms in homes that could benefit from removal of $PM_{2.5}$ In particular, kitchens are often the rooms with the highest peaks in $PM_{2.5}$ due to cooking activities. Research into the impact of extract hoods on PAP effectiveness remains unexplored, and a topic that may be worth investigating given the potentially high exposures to particulates in kitchens.

An observation made during conversations with participants at the site with the MVHR system was the lack of knowledge about this technology. What it did, how, why, or when to operate or maintain it were often unknown by occupants of the flats. Perhaps as a result of this gap in knowledge about the system, compliance with use and maintenance was very poor. Any future work with technologies such as PAPs may experience similar issues and should consider long-term user compliance, user instruction and education, maintenance and replacement of equipment, and other occupant behaviours that could affect the effectiveness of the device. PAPs are unlikely to be a simple, “hands-off” solution to poor IAQ, and additional research into maintaining use over time will be needed.

Chapter 10 Conclusion and reflections

10.1 Key findings

This thesis aimed to answer and expand upon three primary research questions. How effective are standard, commercially available PAPs at removing $PM_{2.5}$ from indoor air in the context of typical occupant use? Do occupants perceive poor indoor air quality due to $PM_{2.5}$ and does it influence occupant behaviour? What is the potential impact on mortality and life expectancy of PAP use at home?

Findings from the work presented in this thesis provided answers to those main questions, and led to meaningful new results that have added to the study of IAQ and health.

- Results from air quality monitoring showed that $PM_{2.5}$ concentrations in bedrooms were reduced with PAP use. The mean reduction in concentration was 45% after 90 minutes of run time.
- Residents were generally dissatisfied with many of the conditions in their homes in summer, with high temperatures over which they did not have sufficient control being the biggest complaint. There was no correlation found between dissatisfaction with air quality, or PAP use, and increased levels of $PM_{2.5}$. High indoor temperatures were the primary driver of PAP use. Poor air quality, however, can and does persist regardless of indoor temperature. Therefore, other motivations for PAP use, or other means of control, need to be considered if air purifiers are to be used for year-round removal of particulate matter.

- The central scenario of the health model showed an increase in the number of years of life (YLG) in the UK of roughly 23 million over the modelled period. This YLG translated to an additional 138 and 120 days of life expectancy for males and females, respectively. Health impacts of reductions to exposure on childhood asthma were also estimated, and the number of QALYs saved by using air purifiers in the bedrooms of children during sleep was estimated to be 1,116 per 10,000 children annually.

The use of portable air purifiers to reduce $PM_{2.5}$ could help to mitigate the negative health effects of exposure whilst at home if occupant behaviour towards the devices could be better managed to reflect indoor air pollution levels rather than thermal conditions. Additionally, areas of potential future research on the use and impact of PAPs and other building systems that reduce $PM_{2.5}$ have been identified through the process of completing this thesis including the role of occupant behaviour on IAQ and its control; integration of filtration systems into controls; and the implications for policy on interventions with PAPs to improve health. The next section will further explore some of these avenues of investigation.

10.2 Reflections

Recent research into risks of exposure to poor indoor air quality indicates that the people who may benefit the most from interventions with PAPs may be least likely to have the economic means to afford PAPs, due to vulnerabilities such as age, health conditions, housing conditions, access to interventions, etc. (Ferguson et al., 2020; Ferguson et al., 2021). The examination of social inequalities with regard to environmental exposures is critical to the effective management of risk. Additionally, the recommendation of PAPs as a principal tool to address population-level $PM_{2.5}$

exposures could be a moral hazard, and create the potential for 'mitigation deterrence', the deprioritisation of sustainable solutions to improve IAQ, particularly those involving elimination of emissions at source (McLaren, 2016). That is, laying the burden of mitigation at the level of the individual, may disincentivise the structural changes, such as the provision of housing with adequate ventilation, or improvements to ambient air quality, that need to be made in policy and at scale. A parallel can be made with the issues of excess winter deaths from cold and how that led to paying for extra fuel rather than solving underlying problems of housing quality (Balfour & Allen, 2014).

As mentioned in discussing the limitations of the work, additional work should be done to understand potential connections between home air purifier use and improvements in health. However, there are challenges that must be considered in the interpretation of the relationships between intervention and outcome. That is, premature mortality is likely to act in conjunction with other risk factors and from exposure to $PM_{2.5}$. Identifying groups of people whose deaths are entirely attributable to $PM_{2.5}$ from air indoor air pollution is not feasible, and this could lead to misinterpretations of the number of deaths that may have been postponed by reductions in $PM_{2.5}$ exposure. That being said, reductions in indoor $PM_{2.5}$ concentration from PAP use were clearly shown in the work presented here, and even small reductions in $PM_{2.5}$ exposure have demonstrated links to health benefits (Boldo et al., 2011).

Novel opportunities exist to link health impact modelling to building physics models that integrate IAQ and energy use. These simulations in parallel could aid in the development of whole building control strategies to improve IAQ without sacrificing thermal comfort or energy performance. Additionally, such co-simulations, and simulations in parallel, can assist in the prioritisation of interventions to better serve populations most at risk of exposure. One challenge of using these types of models to develop policy is that they tend to endorse governance that places emphasis on utilitarian evaluations rather than on the quality of lives of the people most affected. Nonetheless, the benefits for improvements to housing quality, indoor air and the subsequent health outcomes, makes this type of research meaningful across contexts.

References

Aldred, J. R., Darling, E., Morrison, G., Siegel, J., & Corsi, R. L. (2016). Benefit-cost analysis of commercially available activated carbon filters for indoor ozone removal in single-family homes. *Indoor Air, 26*(3), 501-512. doi:10.1111/ina.12220

Allen, R. C., C; Karlen, B; Leckie, S; van Eeden, S; Vedal, S; Wong, I; Brauer, M. (2011). The impact of portable air pilters on indoor air pollution and cardiovascular health in awoodsmoke-impacted community in British Columbia, Canada. *Epidemiology, 22*.

Allen, R. L., Timothy; Sheppard, Lianne; Wallace, Lance; Liu, L. J. Sally. (2003). Use of real-time light scattering data to estimate the contribution of infiltrated and indoor generated particle to indoor air. *Environ Sci Technol, 37*(16), 3484-3492.

Allen, R. W., Carlsten, C., Karlen, B., Leckie, S., van Eeden, S., Vedal, S., . . . Brauer, M. (2011). An air filter intervention study of endothelial function among healthy adults in a woodsmoke-impacted community. *Am J Respir Crit Care Med, 183*(9), 1222-1230. doi:10.1164/rccm.201010-1572OC

Andersen, R., Fabi, V., Toftum, J., Corgnati, S. P., & Olesen, B. W. (2013). Window opening behaviour modelled from measurements in Danish dwellings. *Building and Environment, 69*, 101-113. doi:10.1016/j.buildenv.2013.07.005

Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the air: a review of the effects of particulate matter air pollution on human health. *J Med Toxicol, 8*(2), 166-175. doi:10.1007/s13181-011-0203-1

Arup. (2020). Occupant Satisfaction Evaluation. Retrieved from https://busmethodology.org.uk/

Ashmore, M. R., & Dimitroulopoulou, C. (2009). Personal exposure of children to air pollution. *Atmospheric Environment, 43*(1), 128-141. doi:10.1016/j.atmosenv.2008.09.024

Bai, L., He, Z., Ni, S., Chen, W., Li, N., & Sun, S. (2019). Investigation of PM2.5 absorbed with heavy metal elements, source apportionment and their health impacts in residential houses in the North-east region of China. *Sustainable Cities and Society, 51*. doi:10.1016/j.scs.2019.101690

Balfour, R., & Allen, J. (2014). Local action on health inequalities: Fuel poverty and cold home-related health problems. *Public Health England, London*.

Barn, P., Gombojav, E., Ochir, C., Laagan, B., Beejin, B., Naidan, G., . . . Allen, R. W. (2018). The effect of portable HEPA filter air cleaners on indoor PM2.5 concentrations and second hand tobacco smoke exposure among pregnant women in Ulaanbaatar, Mongolia: The UGAAR randomized controlled trial. *Sci Total Environ, 615*, 1379-1389. doi:10.1016/j.scitotenv.2017.09.291

Barn, P., Larson, T., Noullett, M., Kennedy, S., Copes, R., & Brauer, M. (2008). Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness. *J Expo Sci Environ Epidemiol, 18*(5), 503-511. doi:10.1038/sj.jes.7500640

Batterman, S., Du, L., Mentz, G., Mukherjee, B., Parker, E., Godwin, C., . . . Lewis, T. (2012). Particulate matter concentrations in residences: an intervention study evaluating stand-alone filters and air conditioners. *Indoor Air, 22*(3), 235-252. doi:10.1111/j.1600-0668.2011.00761.x

Bekö, G., Clausen, G., & Weschler, C. J. (2008). Is the use of particle air filtration justified? Costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity. *Building and Environment, 43*(10), 1647-1657. doi:10.1016/j.buildenv.2007.10.006

Ben-David, T., & Waring, M. S. (2018). Interplay of ventilation and filtration: Differential analysis of cost function combining energy use and indoor exposure to PM 2.5 and ozone. *Building and Environment, 128*, 320-335. doi:10.1016/j.buildenv.2017.10.025

Blair, P. S., Humphreys, J. S., Gringras, P., Taheri, S., Scott, N., Emond, A., . . . Fleming, P. J. (2012). Childhood sleep duration and associated demographic characteristics in an English cohort. *Sleep, 35*(3), 353-360. doi:10.5665/sleep.1694

Bo, M., Salizzoni, P., Clerico, M., & Buccolieri, R. (2017). Assessment of indoor-outdoor particulate matter air pollution: a review. *Atmosphere, 8*(8), 136.

Boldo, E., Linares, C., Lumbreras, J., Borge, R., Narros, A., Garcia-Perez, J., . . . Lopez-Abente, G. (2011). Health impact assessment of a reduction in ambient PM(2.5) levels in Spain. *Environ Int, 37*(2), 342-348. doi:10.1016/j.envint.2010.10.004

Boso, À., Álvarez, B., Oltra, C., Garrido, J., Muñoz, C., & Galvez-García, G. (2020). The Grass Is Always Greener on My Side: A Field Experiment Examining the Home Halo Effect. *Sustainability, 12*(16). doi:10.3390/su12166335

Brauner, E. V., Forchhammer, L., Moller, P., Barregard, L., Gunnarsen, L., Afshari, A., . . . Loft, S. (2008). Indoor particles affect vascular function in the aged: an air filtration-based intervention study. *Am J Respir Crit Care Med, 177*(4), 419-425. doi:10.1164/rccm.200704-632OC

Breen, M. S., Schultz, B. D., Sohn, M. D., Long, T., Langstaff, J., Williams, R., . . . Smith, L. (2014). A review of air exchange rate models for air pollution exposure assessments. *Journal of Exposure Science and Environmental Epidemiology, 24*(6), 555-563. doi:10.1038/jes.2013.30

Brehmer, C., Norris, C., Barkjohn, K. K., Bergin, M. H., Zhang, J., Cui, X., . . . Schauer, J. J. (2019). The impact of household air cleaners on the oxidative potential of PM2.5 and the role of metals and sources associated with indoor and outdoor exposure. *Environmental Research*. doi:10.1016/j.envres.2019.108919

Brugge, D., Simon, M. C., Hudda, N., Zellmer, M., Corlin, L., Cleland, S., . . . Durant, J. L. (2017). Lessons from in-home air filtration intervention trials to reduce urban ultrafine particle number concentrations. *Build Environ, 126*, 266-275. doi:10.1016/j.buildenv.2017.10.007

Brunekreef, B., Janssen, N., de Hartog, J. J., Oldenwening, M., Meliefste, K., Hoek, G., . . . Pekkanen, J. (2005). Personal, indoor, and outdoor exposures to PM2. 5 and its components for groups of cardiovascular patients in Amsterdam and Helsinki. *Research report (Health Effects Institute)*(127), 1-70; discussion 71.

Butz, A. M., E; Breysse, P. (2011). A Randomized Trial of Air Cleaners and a Health Coach to Improve Indoor Air Quality for Inner-City Children With Asthma and Secondhand Smoke Exposure. *Archives of Pediatrics & Adolescent Medicine, 165*(8), 741-748.

Buysse, D. J., Reynolds III, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry research, 28*(2), 193-213.

Calì, D., Andersen, R. K., Müller, D., & Olesen, B. W. (2016). Analysis of occupants' behavior related to the use of windows in German households. *Building and Environment, 103*, 54-69.

Chatzidiakou, L., Mumovic, D., & Summerfield, A. (2015). Is CO2 a good proxy for indoor air quality in classrooms? Part 2: Health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics. *Building Services Engineering Research and Technology, 36*(2), 162-181. doi:10.1177/0143624414566245

Cheek, E., Guercio, V., Shrubsole, C., & Dimitroulopoulou, S. (2021). Portable air purification: Review of impacts on indoor air quality and health. *Sci Total Environ, 766*, 142585. doi:10.1016/j.scitotenv.2020.142585

Chen, R., Li, H., Cai, J., Wang, C., Lin, Z., Liu, C., . . . Kan, H. (2018). Fine Particulate Air Pollution and the Expression of microRNAs and Circulating Cytokines Relevant to Inflammation, Coagulation, and Vasoconstriction. *Environ Health Perspect, 126*(1), 017007. doi:10.1289/EHP1447

Chen, R., Meng, X., Zhao, A., Wang, C., Yang, C., Li, H., . . . Kan, H. (2016). DNA hypomethylation and its mediation in the effects of fine particulate air pollution on cardiovascular biomarkers: A randomized crossover trial. *Environment International, 94*, 614-619. doi:https://doi.org/10.1016/j.envint.2016.06.026

Chen, R., Zhao, A., Chen, H., Zhao, Z., Cai, J., Wang, C., . . . Kan, H. (2015). Cardiopulmonary benefits of reducing indoor particles of outdoor origin: a randomized, double-blind crossover trial of air purifiers. *J Am Coll Cardiol, 65*(21), 2279-2287. doi:10.1016/j.jacc.2015.03.553

Cheng, K. C., Park, H. K., Tetteh, A. O., Zheng, D., Ouellette, N. T., Nadeau, K. C., & Hildemann, L. M. (2016). Mixing and sink effects of air purifiers on indoor PM2.5 concentrations: A pilot study of eight residential homes in Fresno, California. *Aerosol Science and Technology, 50*(8), 835-845. doi:10.1080/02786826.2016.1197375

Chi, R., Chen, C., Li, H., Pan, L., Zhao, B., Deng, F., & Guo, X. (2019). Different health effects of indoor-and outdoor-originated PM2. 5 on cardiopulmonary function in COPD patients and healthy elderly adults. *Indoor Air, 29*(2), 192-201.

Climate Change Committee. (2020). *The Sixth Carbon Budget: Buildings*. Retrieved from https://www.theccc.org.uk/publication/sixth-carbon-budget/

Cohen, R., Standeven, M., Bordass, B., & Leaman, A. (2001). Assessing building performance in use 1: the Probe process. *Building Research & Information, 29*(2), 85-102. doi:10.1080/09613210010008018

COMEAP. (2010). *The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom*. Retrieved from London, UK: http://comeap.org.uk/documents/reports/128-the-mortality-effects-of-long-term-exposure-to-particulate-air-pollution-in-the-uk.html

Cooper, E., Wang, Y., Stamp, S., Burman, E., & Mumovic, D. (2021a). Use of portable air purifiers in homes: Operating behaviour, effect on indoor PM2.5 and perceived indoor air quality. *Building and Environment, 191*, 107621. doi:https://doi.org/10.1016/j.buildenv.2021.107621

Cooper, E., Wang, Y., Stamp, S., & Mumovic, D. (2021b). *Health benefits of the use of portable air purifiers that reduce exposure to PM2. 5 in residences: The case of childhood asthma in London*.

Cox, J., Isiugo, K., Ryan, P., Grinshpun, S. A., Yermakov, M., Desmond, C., . . . Reponen, T. (2018). Effectiveness of a portable air cleaner in removing aerosol particles in homes close to highways. *Indoor Air, 28*(6), 818-827. doi:10.1111/ina.12502

Coyle, D., Stieb, D., Burnett, R., DeCivita, P., Krewski, D., Chen, Y., & Thun, M. (2003). Impact of particulate air pollution on quality-adjusted life expectancy in Canada. *Journal of Toxicology and Environmental Health Part A, 66*(16-19), 1847-1864.

Crilley, L. R., Shaw, M., Pound, R., Kramer, L. J., Price, R., Young, S., . . . Pope, F. D. (2018). Evaluation of a low-cost optical particle counter (Alphasense OPC-N2) for ambient air monitoring. *Atmospheric Measurement Techniques, 11*(2), 709-720. doi:10.5194/amt-11-709-2018

Crouse, D. L., Peters, P. A., van Donkelaar, A., Goldberg, M. S., Villeneuve, P. J., Brion, O., . . . Burnett, R. T. (2012). Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study. *Environ Health Perspect, 120*(5), 708-714. doi:10.1289/ehp.1104049

Cui, X., Li, F., Xiang, J., Fang, L., Chung, M. K., Day, D. B., . . . Zhang, J. J. (2018). Cardiopulmonary effects of overnight indoor air filtration in healthy non-smoking adults: A double-blind randomized crossover study. *Environ Int, 114*, 27-36. doi:10.1016/j.envint.2018.02.010

Davies, M., & Oreszczyn, T. (2012). The unintended consequences of decarbonising the built environment: A UK case study. *Energy and Buildings, 46*, 80-85. doi:10.1016/j.enbuild.2011.10.043

Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., . . . Kjærgaard, M. B. (2020). A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort. *Building and Environment, 178*, 106920.

Day, J. K., & O'Brien, W. (2017). Oh behave! Survey stories and lessons learned from building occupants in high-performance buildings. *Energy Research & Social Science, 31*, 11-20. doi:https://doi.org/10.1016/j.erss.2017.05.037

Defra. (2021). Table 7: Annual concentrations of PM2.5 in the UK, 2009 to 2020. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/980398/Table07.csv/preview

Delgado, A., Flor, H., & Ieee. (2017). *Selection of the best air purifier system to urban houses using AHP*. New York: Ieee.

Di, Q., Dai, L., Wang, Y., Zanobetti, A., Choirat, C., Schwartz, J. D., & Dominici, F. (2017). Association of short-term exposure to air pollution with mortality in older adults. *JAMA, 318*(24), 2446-2456.

Dimitroulopoulou, C. (2012). Ventilation in European dwellings: A review. *Building and Environment, 47*, 109-125. doi:10.1016/j.buildenv.2011.07.016

Dimitroulopoulou, C., Crump, D., Coward, S., Brown, B., Squire, R., Mann, H., . . . Ross, D. (2005). Ventilation, air tightness and indoor air quality in new homes. *BR477, BRE Bookshop*.

Dockery, D. W., Pope, C. A., Xu, X., Spengler, J. D., Ware, J. H., Fay, M. E., . . . Speizer, F. E. (1993). An association between air pollution and mortality in six US cities. *New England journal of medicine, 329*(24), 1753-1759.

Dyer, C. (2020). Air pollution from road traffic contributed to girl's death from asthma, coroner concludes. *BMJ, 371*, m4902. doi:10.1136/bmj.m4902

Eggleston, P. A., Butz, A., Rand, C., Curtin-Brosnan, J., Kanchanaraksa, S., Swartz, L., . . . Krishnan, J. A. (2005). Home environmental intervention in inner-city asthma: a randomized controlled clinical trial. *Annals of Allergy, Asthma & Immunology, 95*(6), 518-524. doi:https://doi.org/10.1016/S1081-1206(10)61012-5

Fang, L. W., D; Clausen, G; Fanger, P. (2004). Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. *Indoor Air, 14*, 74-81.

Fanger, P. O. (1988). Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. *Energy and Buildings, 12*(1), 1-6.

Ferguson, L., Taylor, J., Davies, M., Shrubsole, C., Symonds, P., & Dimitroulopoulou, S. (2020). Exposure to indoor air pollution across socio-economic groups in high-income countries: A scoping review of the literature and a modelling methodology. *Environment International, 143*, 105748.

Ferguson, L., Taylor, J., Zhou, K., Shrubsole, C., Symonds, P., Davies, M., & Dimitroulopoulou, S. (2021). Systemic inequalities in indoor air pollution exposure in London, UK. *Buildings and Cities, 2*(1).

Fisk, W. J. (2013). Health benefits of particle filtration. *Indoor Air, 23*(5), 357-368. doi:10.1111/ina.12036

Fisk, W. J. (2018). How home ventilation rates affect health: A literature review. *Indoor Air, 28*(4), 473-487. doi:10.1111/ina.12469

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

Fisk, W. J., & Chan, W. R. (2017b). Health benefits and costs of filtration interventions that reduce indoor exposure to PM2.5 during wildfires. *Indoor Air, 27*(1), 191-204. doi:10.1111/ina.12285

Gehring, U., Wijga, A. H., Brauer, M., Fischer, P., de Jongste, J. C., Kerkhof, M., . . . Brunekreef, B. (2010). Traffic-related air pollution and the development of asthma and allergies during the first 8 years of life. *Am J Respir Crit Care Med, 181*(6), 596-603. doi:10.1164/rccm.200906-0858OC

Gotschi, T., Oglesby, L., Mathys, P., Monn, C., Manalis, N., Koistinen, K., . . . Kunzli, N. (2002). Comparison of black smoke and PM2.5 levels in indoor and outdoor environments of four European cities. *Environmental Science and Technology, 36*(6), 1191-1197. doi:10.1021/es010079n

Gupta, R., & Kapsali, M. (2016). Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK. *Advances in Building Energy Research, 10*(1), 46-68.

Hamilton, I., Milner, J., Chalabi, Z., Das, P., Jones, B., Shrubsole, C., . . . Wilkinson, P. (2015). Health effects of home energy efficiency interventions in England: a modelling study. *Bmj Open, 5*(4), e007298. doi:10.1136/bmjopen-2014-007298

Hanninen, O. P., J; Tuomisto, J; Yli-Tuomi, T; Seppanen, O; Jantunen, M. (2005). Reduction potential of urban PM2.5 mortality risk using modern ventilation systems in buildings. *Indoor Air, 15*, 246-256.

Hart, J. F., Ward, T. J., Spear, T. M., Rossi, R. J., Holland, N. N., & Loushin, B. G. (2011). Evaluating the effectiveness of a commercial portable air purifier in homes with wood burning stoves: A preliminary study. *Journal of Environmental and Public Health, 2011*. doi:10.1155/2011/324809

HM Government. (2010). *Approved Document F (AD F) F1 Means of Ventilation of the UK Building Regulations for all Building Types in the UK.* Retrieved from

https://www.gov.uk/government/publications/ventilation-approved-document-f
Huang, C.-H., Xiang, J., Austin, E., Shirai, J., Liu, Y., Simpson, C., . . . Seto, E. (2020). Impacts of using auto-mode portable air cleaner on indoor PM2.5 levels: An intervention study. *Building and Environment*. doi:10.1016/j.buildenv.2020.107444
Hussein, T., Korhonen, H., Herrmann, E., Hämeri, K., Lehtinen, K. E. J., & Kulmala, M. (2005). Emission Rates Due to Indoor Activities: Indoor Aerosol Model Development, Evaluation, and Applications. *Aerosol Science and Technology, 39*(11), 1111-1127. doi:10.1080/02786820500421513
James, C., Bernstein, D. I., Cox, J., Ryan, P., Wolfe, C., Jandarov, R., . . . Reponen, T. (2019). HEPA filtration improves asthma control in children exposed to traffic-related airborne particles. *Indoor Air*. doi:10.1111/ina.12625
Jenkinson, C., Layte, R., Jenkinson, D., Lawrence, K., Petersen, S., Paice, C., & Stradling, J. (1997). A shorter form health survey: can the SF-12 replicate results from the SF-36 in longitudinal studies? *Journal of Public Health, 19*(2), 179-186. doi:10.1093/oxfordjournals.pubmed.a024606
Jeong, B., Jeong, J.-W., & Park, J. (2016). Occupant behavior regarding the manual control of windows in residential buildings. *Energy and Buildings, 127*, 206-216.
Jones, C. H., & Ball, H. (2014). Exploring Socioeconomic Differences in Bedtime Behaviours and Sleep Duration in English Preschool Children. *Infant Child Dev, 23*(5), 518-531. doi:10.1002/icd.1848
Kajbafzadeh, M., Brauer, M., Karlen, B., Carlsten, C., Van Eeden, S., & Allen, R. W. (2015). The impacts of traffic-related and woodsmoke particulate matter on measures of cardiovascular health: A HEPA filter intervention study. *Occupational and Environmental Medicine, 72*(6), 394-400. doi:10.1136/oemed-2014-102696
Karottki, D. S., M; Frederiksen, M. (2013). An indoor air filtration study in homes of elderly: cardiovascular and respiratory effects of exposure to particulate matter. *Environmental Health 12*, 116-225.
Kearney, J., Wallace, L., MacNeill, M., Héroux, M.-E., Kindzierski, W., & Wheeler, A. (2014). Residential infiltration of fine and ultrafine particles in Edmonton. *Atmospheric Environment, 94*, 793-805. doi:10.1016/j.atmosenv.2014.05.020
Kelly, F. J., & Fussell, J. C. (2019). Improving indoor air quality, health and performance within environments where people live, travel, learn and work. *Atmospheric Environment, 200*, 90-109. doi:10.1016/j.atmosenv.2018.11.058
Klepeis, N. N., W; Ott, W. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal ofExposure Analysis and Environmental Epidemiology, 11*(3), 231-252.
Laden, F., Schwartz, J., Speizer, F. E., & Dockery, D. W. (2006). Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities study. *Am J Respir Crit Care Med, 173*(6), 667-672. doi:10.1164/rccm.200503-443OC
Lai, H. K., Kendall, M., Ferrier, H., Lindup, I., Alm, S., Hänninen, O., . . . Ashmore, M. (2004). Personal exposures and microenvironment concentrations of PM2. 5, VOC, NO2 and CO in Oxford, UK. *Atmospheric Environment, 38*(37), 6399-6410.

Langer, S., Ramalho, O., Le Ponner, E., Derbez, M., Kirchner, S., & Mandin, C. (2017). Perceived indoor air quality and its relationship to air pollutants in French dwellings. *Indoor Air, 27*(6), 1168-1176. doi:10.1111/ina.12393

Leksell, I., & Rabl, A. (2001). Air pollution and mortality: quantification and valuation of years of life lost. *Risk Analysis, 21*(5), 843-843.

Li, H., Cai, J., Chen, R., Zhao, Z., Ying, Z., Wang, L., . . . Kan, H. (2017). Particulate Matter Exposure and Stress Hormone Levels: A Randomized, Double-Blind, Crossover Trial of Air Purification. *Circulation, 136*(7), 618-627. doi:10.1161/CIRCULATIONAHA.116.026796

Liu, S., Chen, J., Zhao, Q., Song, X., Shao, D., Meliefste, K., . . . Huang, W. (2018a). Cardiovascular benefits of short-term indoor air filtration intervention in elderly living in Beijing: An extended analysis of BIAPSY study. *Environmental Research, 167*, 632-638. doi:https://doi.org/10.1016/j.envres.2018.08.026

Liu, T., Cai, Y. Y., Feng, B. X., Cao, G. X., Lin, H. L., Xiao, J. P., . . . Ma, W. J. (2018b). Long-term mortality benefits of air quality improvement during the twelfth five-year-plan period in 31 provincial capital cities of China. *Atmospheric Environment, 173*, 53-61. doi:10.1016/j.atmosenv.2017.10.054

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. *Environ Health Perspect, 120*(2), 216-222. doi:10.1289/ehp.1104035

Macintosh, D. L., Minegishi, T., Kaufman, M., Baker, B. J., Allen, J. G., Levy, J. I., & Myatt, T. A. (2010). The benefits of whole-house in-duct air cleaning in reducing exposures to fine particulate matter of outdoor origin: a modeling analysis. *J Expo Sci Environ Epidemiol, 20*(2), 213-224. doi:10.1038/jes.2009.16

Maestas, M. M., Brook, R. D., Ziemba, R. A., Li, F., Crane, R. C., Klaver, Z. M., . . . Morishita, M. (2019). Reduction of personal PM2.5 exposure via indoor air filtration systems in Detroit: an intervention study. *J Expo Sci Environ Epidemiol, 29*(4), 484-490. doi:10.1038/s41370-018-0085-2

Mavrogianni, A., Davies, M., Taylor, J., Oikonomou, E., Raslan, R., Biddulph, P., . . . Shrubsole, C. (2013). The unintended consequences of energy efficient retrofit on indoor air pollution and overheating risk in a typical Edwardian mid-terraced house. *Future Build.*

McDonald, E., Cook, D., Newman, T., Griffith, L., Cox, G., & Guyatt, G. (2002). Effect of Air Filtration Systems on Asthma. *Chest, 122*(5), 1535-1542. doi:10.1378/chest.122.5.1535

McLaren, D. (2016). Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Future, 4*(12), 596-602.

McNamara, M. L., Thornburg, J., Semmens, E. O., Ward, T. J., & Noonan, C. W. (2017). Reducing indoor air pollutants with air filtration units in wood stove homes. *Sci Total Environ, 592*, 488-494. doi:10.1016/j.scitotenv.2017.03.111

Miller, B., & Hurley, J. (2003). Life table methods for quantitative impact assessments in chronic mortality. *Journal of Epidemiology & Community Health, 57*(3), 200-206.

Miller, B. a. H., F. (2010). Technical Aspects of Life Table Analyses. Supporting paper for the 2010

COMEAP Report. Retrieved from https://www.gov.uk/government/publications/comeap-mortality-effects-of-long-term-exposure-to-particulate-air-pollution-in-the-uk

Milner, J., Chalabi, Z., Vardoulakis, S., & Wilkinson, P. (2015). Housing interventions and health: Quantifying the impact of indoor particles on mortality and morbidity with disease recovery. *Environ Int, 81*, 73-79. doi:10.1016/j.envint.2015.04.011

Mølhave, L., Liu, Z., Jørgensen, A. H., Pedersen, O. F., & Kjægaard, S. K. (1993). Sensory And Physiological Effects On Humans Of Combined Exposures To Air Temperatures And Volatile Organic Compounds. *Indoor Air, 3*(3), 155-169. doi:https://doi.org/10.1111/j.1600-0668.1993.t01-1-00002.x

Morishita, M., Adar, S. D., D'Souza, J., Ziemba, R. A., Bard, R. L., Spino, C., & Brook, R. D. (2018). Effect of Portable Air Filtration Systems on Personal Exposure to Fine Particulate Matter and Blood Pressure Among Residents in a Low-Income Senior Facility: A Randomized Clinical Trial. *JAMA Intern Med, 178*(10), 1350-1357. doi:10.1001/jamainternmed.2018.3308

Murray, C. J., Aravkin, A. Y., Zheng, P., Abbafati, C., Abbas, K. M., Abbasi-Kangevari, M., . . . Abdollahpour, I. (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet, 396*(10258), 1223-1249.

Noonan, C. W., Semmens, E. O., Smith, P., Harrar, S. W., Montrose, L., Weiler, E., . . . Ward, T. J. (2017). Randomized trial of interventions to improve childhood asthma in homes with wood-burning stoves. *Environmental Health Perspectives, 125*(9). doi:10.1289/EHP849

Novoselac, A., & Siegel, J. A. (2009). Impact of placement of portable air cleaning devices in multizone residential environments. *Building and Environment, 44*(12), 2348-2356. doi:10.1016/j.buildenv.2009.03.023

Office of the Deputy Prime Minister. (2006). *Housing Health and Safety Rating System*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/9425/150940.pdf

ONS. (2019). Deaths Retrieved from https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths

Ostro, B. R., S. (1989). Air pollution and acute respiratory morbidity: An observational study of multiple pollutants. *Environ Res, 50*, 238-247.

Park, H. K., Cheng, K. C., Tetteh, A. O., Hildemann, L. M., & Nadeau, K. C. (2017). Effectiveness of air purifier on health outcomes and indoor particles in homes of children with allergic diseases in Fresno, California: A pilot study. *J Asthma, 54*(4), 341-346. doi:10.1080/02770903.2016.1218011

Pei, J., Dong, C., & Liu, J. (2019). Operating behavior and corresponding performance of portable air cleaners in residential buildings, China. *Building and Environment, 147*, 473-481. doi:10.1016/j.buildenv.2018.08.009

Piazza, T. L., R.; Hayes, J. (2006). *Survey of the use of ozone-generating air cleaners by the California public*. Retrieved from California:

Pinto, J. P., Lefohn, A. S., & Shadwick, D. S. (2004). Spatial variability of PM2. 5 in urban areas in the United States. *Journal of the Air & Waste Management Association, 54*(4), 440-449.

Pope, C. A., 3rd, & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. *J Air Waste Manag Assoc, 56*(6), 709-742. doi:10.1080/10473289.2006.10464485

Pope, C. A., Coleman, N., Pond, Z. A., & Burnett, R. T. (2020). Fine particulate air pollution and human mortality: 25+ years of cohort studies. *Environmental Research, 183*, 108924.

Pope, C. A., Lefler, J. S., Ezzati, M., Higbee, J. D., Marshall, J. D., Kim, S. Y., . . . Burnett, R. T. (2019). Mortality Risk and Fine Particulate Air Pollution in a Large, Representative Cohort of US Adults. *Environmental Health Perspectives, 127*(7). doi:10.1289/ehp4438

Pope, C. A. B., Richard; Thun, Michael; Calle, Eugenia; Krewski, Daniel; Ito, Kazuhiko; Thurston, George. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA, 287*, 1132-1141.

Qiu, H., Yu, H., Wang, L., Zhu, X., Chen, M., Zhou, L., . . . Pan, J. (2018). The burden of overall and cause-specific respiratory morbidity due to ambient air pollution in Sichuan Basin, China: A multi-city time-series analysis. *Environ Res, 167*, 428-436. doi:10.1016/j.envres.2018.08.011

R Core Team. (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. Retrieved from https://www.R-project.org/

Raw, G. J., Coward, S. K., Brown, V. M., & Crump, D. R. (2004). Exposure to air pollutants in English homes. *Journal of Exposure Science & Environmental Epidemiology, 14*(1), S85-S94.

Reisman, R. (2001). Do air cleaners make a difference in treating allergic disease in homes? *Annals Allergy Asthma Immunology, 87*, 41-43.

Reshetin, V., & Kazazyan, V. (2004). Public-health impact of outdoor air pollution in Russia. *Environmental Modeling & Assessment, 9*(1), 43-50.

Rice, J. L., Brigham, E., Dineen, R., Muqueeth, S., O'Keefe, G., Regenold, S., . . . Diette, G. B. (2018). The feasibility of an air purifier and secondhand smoke education intervention in homes of inner city pregnant women and infants living with a smoker. *Environmental Research, 160*, 524-530. doi:10.1016/j.envres.2017.10.020

Rijal, H. B., Tuohy, P., Humphreys, M. A., Nicol, J. F., Samuel, A., Raja, I. A., & Clarke, J. (2008). Development of adaptive algorithms for the operation of windows, fans, and doors to predict thermal comfort and energy use in Pakistani buildings. *American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Transactions, 114*(2), 555-573.

Rotko, T. O., L.; Kunzli, N.; Carrer, P.; Nieuwenhuijsen, M.; Jantunen, M. (2002). Determinants of perceived air pollution annoyance and association between annoyance scores and air pollution (PM2.5, NO2) concentrations in the European EXPOLIS study. *Atmos Environ, 36*, 4593-4602.

Samet, J. (1993). Indoor air pollution: A public health perspective. *Indoor Air, 3*, 219-226.

Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environ Health Perspect, 120*(12), 1671-1677. doi:10.1289/ehp.1104789

Schwartz, J. S., D; Larson, T; Pierson, L; Koenig, J. (1993). Particulate air pollution and hospital emergency room visits for asthma in Seattle. *Am Rev Respir Dis, 147*, 826-831.

Schweiker, M., Ampatzi, E., Andargie, M. S., Andersen, R. K., Azar, E., Barthelmes, V. M., . . . Zhang, S. (2020). Review of multi-domain approaches to indoor environmental perception and behaviour. *Building and Environment, 176*. doi:10.1016/j.buildenv.2020.106804

Shao, D. Q., Du, Y. P., Liu, S., Brunekreef, B., Meliefste, K., Zhao, Q., . . . Huang, W. (2017). Cardiorespiratory responses of air filtration: A randomized crossover intervention trial in seniors living in Beijing Beijing Indoor Air Purifier StudY, BIAPSY. *Science of the Total Environment, 603*, 541-549. doi:10.1016/j.scitotenv.2017.06.095

Shaughnessy, R. J., & Sextro, R. G. (2006). What is an effective portable air cleaning device? A review. *Journal of Occupational and Environmental Hygiene, 3*(4), 169-181. doi:10.1080/15459620600580129

Shrubsole, C., MacMillan, A., Davies, M., May, N. (2014). 100 Unintended consequences of policies to improve energy efficiency of the UK housing stock. *Indoor and Built Environment, 23*(3), 340-352.

Shrubsole, C., Ridley, I., Biddulph, P., Milner, J., Vardoulakis, S., Ucci, M., . . . Davies, M. (2012). Indoor PM2.5 exposure in London's domestic stock: Modelling current and future exposures following energy efficient refurbishment. *Atmospheric Environment, 62*, 336-343. doi:10.1016/j.atmosenv.2012.08.047

Spilak, M. P., Karottki, G. D., Kolarik, B., Frederiksen, M., Loft, S., & Gunnarsen, L. (2014). Evaluation of building characteristics in 27 dwellings in Denmark and the effect of using particle filtration units on PM2.5 concentrations. *Building and Environment, 73*, 55-63. doi:10.1016/j.buildenv.2013.11.020

Sublett, J. L. (2011). Effectiveness of air filters and air cleaners in allergic respiratory diseases: a review of the recent literature. *Curr Allergy Asthma Rep, 11*(5), 395-402. doi:10.1007/s11882-011-0208-5

Toftum, J., Thorseth, A., Markvart, J., & Logadóttir, Á. (2018). Occupant response to different correlated colour temperatures of white LED lighting. *Building and Environment, 143*, 258-268. doi:https://doi.org/10.1016/j.buildenv.2018.07.013

Torresin, S., Pernigotto, G., Cappelletti, F., & Gasparella, A. (2018). Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works. *Indoor Air, 28*(4), 525-538.

USEPA. (2011). *The costs and benefits of the clean air act: 1990 to 2020*. Retrieved from

Vyas, S., Srivastav, N., & Spears, D. (2016). An experiment with air purifiers in delhi during winter 2015-2016. *Plos One, 11*(12). doi:10.1371/journal.pone.0167999

Wallace, L. (2008). *Effectiveness of home air cleaners in reducing indoor levels of particles*. Retrieved from

Wang, B. Y., Eum, K. D., Kazemiparkouhi, F., Li, C., Manjourides, J., Pavlu, V., & Suh, H. (2020). The impact of long-term PM2.5 exposure on specific causes of death: exposure-response curves and effect modification among 53 million US Medicare beneficiaries. *Environmental Health, 19*(1). doi:10.1186/s12940-020-00575-0

Ward, T. J., Semmens, E. O., Weiler, E., Harrar, S., & Noonan, C. W. (2017). Efficacy of interventions targeting household air pollution from residential wood stoves. *Journal of Exposure Science and Environmental Epidemiology, 27*(1), 64-71. doi:10.1038/jes.2015.73

Wei, Y., Wang, Y., Di, Q., Choirat, C., Wang, Y., Koutrakis, P., . . . Schwartz, J. D. (2019). Short term exposure to fine particulate matter and hospital admission risks and costs in the Medicare population: time stratified, case crossover study. *BMJ, 367*.

Weichenthal, S., Mallach, G., Kulka, R., Black, A., Wheeler, A., You, H., . . . Sharp, D. (2013). A randomized double-blind crossover study of indoor air filtration and acute changes in cardiorespiratory health in a First Nations community. *Indoor Air, 23*(3), 175-184. doi:10.1111/ina.12019

Weisel, C. P., Zhang, J., Turpin, B. J., Morandi, M. T., Colome, S., Stock, T. H., . . . Shendell, D. (2005). Relationship of Indoor, Outdoor and Personal Air (RIOPA) study: study design, methods and quality assurance/control results. *J Expo Anal Environ Epidemiol, 15*(2), 123-137. doi:10.1038/sj.jea.7500379

Whitby, K. T. A., G.R.; Rubow, K.L. (1983). Dynamic model for evaluating room-sized air cleaners. *ASHRAE Transactions, 89-2A*, 172-182.

WHO. (2019). Global Burden of Disease. Retrieved from https://www.who.int/data/gho/data/themes/mortality-and-global-health-estimates

Witterseh, T., Wyon, D. P., & Clausen, G. (2004). The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work. *Indoor Air, 14*(8), 30-40.

Wu, J., Liu, C., Li, H., Ouyang, D., Cheng, J., Wang, Y., & You, S. (2017). Residential air-conditioner usage in China and efficiency standardization. *Energy, 119*, 1036-1046. doi:10.1016/j.energy.2016.11.038

Yang, B. Y., Qian, Z., Howard, S. W., Vaughn, M. G., Fan, S. J., Liu, K. K., & Dong, G. H. (2018). Global association between ambient air pollution and blood pressure: A systematic review and meta-analysis. *Environ Pollut, 235*, 576-588. doi:10.1016/j.envpol.2018.01.001

Yao, M., & Zhao, B. (2017). Window opening behavior of occupants in residential buildings in Beijing. *Building and Environment, 124*, 441-449. doi:10.1016/j.buildenv.2017.08.035

Yuan, Y., Luo, Z., Liu, J., Wang, Y., & Lin, Y. (2018). Health and economic benefits of building ventilation interventions for reducing indoor PM2.5 exposure from both indoor and outdoor origins in urban Beijing, China. *Science of the Total Environment, 626*, 546-554. doi:10.1016/j.scitotenv.2018.01.119

Zhan, Y., Johnson, K., Norris, C., Shafer, M. M., Bergin, M. H., Zhang, Y., . . . Schauer, J. J. (2018). The influence of air cleaners on indoor particulate matter components and oxidative potential in residential households in Beijing. *Science of the Total Environment, 626*, 507-518. doi:10.1016/j.scitotenv.2018.01.024

Zhang, Y., Mo, J., Li, Y., Sundell, J., Wargocki, P., Zhang, J., . . . Sun, Y. (2011). Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. *Atmospheric Environment, 45*(26), 4329-4343. doi:10.1016/j.atmosenv.2011.05.041

Zuraimi, S. (2007). Estimates of associated outdoor particulate matter health risk and costs reductions from alternative building, ventilation and filtration scenarios.

Science of the Total Environment, 377(1), 1-11. doi:10.1016/j.scitotenv.2007.01.090