Ventilation in occupied homes: measurement, performance and sociotechnical perspectives

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I, Jessica Frances Mary Few, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Abstract

In the UK, steps have been taken to reduce air permeability of buildings and reduce their energy consumption due to unplanned ventilation. However, adequate ventilation is required for good indoor air quality. The building regulations require means for adequate ventilation in new buildings for good indoor air quality, and in England Approved Document F (ADF) sets out how this may be achieved. Nonetheless, few detailed studies of ventilation in occupied homes have been carried out. This project addresses aspects of ventilation measurement, performance of ventilation systems and the sociotechnical nature of ventilation in occupied homes.

Ventilation in occupied buildings is driven by building characteristics, ventilation equipment, weather conditions and occupant actions and therefore can be highly variable. Despite this, much ventilation research in occupied homes either measures a long-term average ventilation rate or collects a small number of 'snapshot' measurements of ventilation rate. This research developed a method for measuring ventilation rates in occupied homes based on the tracer gas decay technique using metabolic CO_2. The method was applied in four occupied dwellings over 6 months to give more than 500 ventilation rate measurements. These results facilitated assessment of the performance of the ventilation system and exploration of the variation in ventilation rates. This revealed significant differences in the ventilation rates experienced by occupants in the different dwellings and highlighted shortcomings in the planned ventilation system.

Ventilation in occupied homes is strongly influenced by occupants. The final part of the research used a social practice theory framework to compare the participants' practices with the intended uses of ventilation equipment implicit in ADF.

This revealed that although the participants shared many of ADF's goals in terms of the air in their homes, their practices were more nuanced than ADF and that their use of the ventilation equipment did not reflect ADF's intentions.

Impact Statement

The work presented in this thesis has potential impact for academia, policy, industry and public health. Ventilation rates in dwellings are variable due to changes in weather conditions, occupant actions and the operation of mechanical ventilation systems. A method of implementing the tracer gas concentration decay method for measuring ventilation in occupied dwellings using metabolically generated CO_2 was developed in this work. The method developed facilitates measurements of ventilation in occupied homes which could support more frequent, detailed measurements of ventilation rates by researchers interested in drawing out detailed insights into how ventilation is experienced by occupants over time. Additionally, this research has taken a sociotechnical approach to exploring ventilation in occupied homes and in so doing has gained a useful perspective relating to the reasons for the differences in ventilation rates observed in different dwellings. This demonstrated the potential utility of a sociotechnical approach when investigating these issues.

This research has several impacts related to policy governing ventilation systems installed in dwellings. The detailed sociotechnical approach highlighted particular areas where current guidance for ventilation in homes through Approved Document F (ADF) does not reflect the as-occupied reality in homes. For example, the current design of ventilation systems in homes assumes that occupants are aware of harmful pollutants in their home and take action to reduce their concentrations, however pollutants were interpreted differently by different participants and the actions outlined in the guidance did not always happen in practice. The resulting ventilation rates were ‘hit or miss’ and adequate ventilation was not assured for all participants. Additionally, ventilation equipment was not always used in the intended manner, trickle vents were almost always closed and continuous MEV equipment was not always switched on. This suggests further research is needed to explore strategies for encouraging occupants to use ventilation equipment in the intended manner. Developing robust ventilation systems which deliver adequate ventilation rates is challenging given the diverse conditions in homes as-occupied. However, identifying specific issues is an important step in rectifying or addressing them with targeted policies to improve as-occupied ventilation rates and IAQ in the future.

Finally, specific technical issues identified in the studied dwellings suggest areas that should be addressed by policy in the future. These include discrepancies between measured ventilation rates and those inferred from fan flow rates; current commissioning requirements were not found to identify such issues.

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Chapter 1

Introduction

Klepeis et al. (2001) found that people in the US spent 87% of their time indoors and 69% at home. A smaller study in Hertfordshire, UK found 60 office workers spent between 80% - 90% of their time indoors and close to 50% of their time at home (Kornartit et al., 2010). The indoor air quality (IAQ) people experience can have serious implications for their health (NICE, 2020b), this is important given the amount of time people spend indoors. This issue has risen to prominence in the last year given the on-going Covid-19 pandemic and the likely increased risk of virus transmission in poorly ventilated spaces (Bhagat et al., 2020). Increasing ventilation rates can improve IAQ, but can also increase the energy consumption associated with buildings (ASHRAE, 2017b). It is important to reduce building energy consumption in order to meet climate change mitigation goals, for example as noted by CCC (2020) in the UK. Ideal ventilation rates in homes must balance these energy and health considerations. This thesis is about ventilation experienced in occupied homes and this introductory chapter sets the context and outlines the aims and structure of this thesis.

1.1 Energy and ventilation

Countries around the world are committed to reducing their CO_2 emissions through the Paris Agreement (UNFCCC, 2015). The Climate Change Act 2008 (2050 Target Amendment) Order 2019 commits the UK to achieving net zero emissions by 2050. Reductions in UK emissions have thus far have largely been achieved through changes in energy supply, whereas reductions in sectors including residential energy use have been much more gradual (CCC, 2020). In 2015, the domestic sector accounted for 29% of final energy consumption in the UK, and space and water heating made up 80% of this energy use (BEIS, 2016). Reducing the heat load of the built environment is one of the areas identified as essential if the UK is to achieve its carbon reduction targets (CCC, 2020).

CIBSE (2015) state that heat loss through ventilation can account for more than half of the total heat loss from a well-insulated building, although heat loss will vary depending on the building characteristics, actions of the occupants and the weather conditions. Reducing air permeability to reduce heat loss associated with unplanned air leakage has been the subject of various policies since the early 2000's (Love et al., 2017).

Measures to increase energy efficiency and airtightness of buildings can increase indoor pollutant concentrations, leading to potentially damaging health effects. Symonds et al. (2019) found that home energy efficiency measures which tend to increase airtightness and thereby reduce ventilation rates, such as double glazing, loft insulation and wall insulation, were associated with increased radon activity. Further possible unintended consequences of increasing airtightness and associated reduction of ventilation rates include 'a rise in relative humidity leading to increased house dust mites, mould, severity of asthma and allergies' (Shrubsole et al., 2014, p. 344).

1.2 Health and ventilation

Replacing indoor air with outdoor air is necessary to dilute and remove pollutants produced indoors (ASHRAE, 2017b). Indoor air quality (IAQ) is associated with the concentration of pollutants in indoor air, although there is no universally agreed scale for assessing the quality of indoor air (Salis et al., 2017). Common indoor pollutants include volatile organic compounds (VOCs), nitrogen oxides (NO_x), carbon monoxide (CO), formaldehyde, radon, particulate matter (PMs) and biological contaminants (for example mould and house dust mites) (Salis et al., 2017). The Royal

College of Physicians (RCP, 2016) emphasised the importance of improving our understanding of indoor air quality (IAQ) and its relation to health, and highlighted the potentially conflicting goals of improving IAQ and increasing airtightness in dwellings.

Indoor pollutants can have serious consequences for health, with different pollutants having different effects. Radon has been estimated to cause between 1100 and 2900 lung cancer deaths annually in the UK (Health Protection Agency, 2009; Gaskin et al., 2018). Shorter et al. (2018) found that the presence of visible mould and mould odour in dwellings was associated with new onset of childhood wheeze. Shrubsole et al. (2019a) reviewed the literature on the health effects of VOCs identified in indoor environments and found different VOCs have been associated with health effects including cancers, respiratory illness and neurological conditions. Satish et al. (2012) found that decision making performance decreased at CO_2 concentrations of 1000 ppm compared to 600 ppm and at 2500 ppm compared to 1000 ppm. However, Lowe et al. (2018) found that evidence in the literature is mixed and that larger sample sizes are required to draw a definitive conclusions on whether, and at what concentration, there is an effect of CO_2 on human cognition. Jones (1999) noted that different pollutants cause health effects over different time-scales and long-term concentration averaging measurement techniques may be unable to adequately assess the risk for pollutants which pose risks after short-term exposures. Salis et al. (2017) note the difficulties in defining IAQ indices given the variety of pollutants present, the time frames over which measurements are made and exposure limits defined, the ‘cocktail effect’ and the uncertainty in exposure limits.

There have been several studies investigating a link between ventilation rates and health. Fisk (2018) systematically reviewed this literature and concluded that the evidence suggests that increased ventilation rate is associated with better health outcomes, however he was not able to identify a consistent threshold ventilation rate at which better health outcomes were observed. Fisk identified various possible reasons for the inconsistency in the literature, including the variability of pollutants, humidity and ventilation rates in the indoor environments studied. Moreover, the literature Fisk reviewed made use of different ventilation measurement techniques which return ventilation rates averaged over different periods of time. Given that the impact of pollutants on health depend on the time-scale of exposure, averaging ventilation rates over time could mask important effects. Nonetheless, a ventilation rate of 0.5 ach (air changes per hour) is often considered to be a reasonable balance issues of IAQ and energy efficiency (Sundell et al., 2011; Dimitroulopoulou, 2012).

1.3 Ventilation in English dwellings

The UK government has policies and guidance in place with the intention of ensuring adequate ventilation and indoor air quality at the same time as ensuring that newly-built buildings are energy efficient. The Building Regulations for England and Wales require that new buildings have 'adequate means of ventilation provided for the people in the building' (HMG, 2013b, p.4). Approved Document F to the building regulations (ADF) (HMG, 2013b) gives guidance on how this requirement can be met. The stated aim of ventilation according to ADF is to remove 'stale' indoor air and replace this with 'fresh' outdoor air.

ADF gives three ways to comply with the Building Regulations in terms of ventilation. Firstly, by providing the whole dwelling and extract ventilation rates specified in ADF, secondly by installing one of the of four ventilation systems described in ADF (discussed further in Section 2.3), or finally by otherwise demonstrating to the Building Control Body that the requirement for adequate ventilation has been met. Since 2010, commissioning of ventilation systems has been required to confirm that all relevant ventilation equipment has been installed in line with guidance (HMG, 2010c). For example, commissioning includes confirming that mechanical extract ventilation equipment provides flow rates in line with the guidance.

1.4 Performance gaps

The guidance provided by ADF is intended to ensure that adequate ventilation rates are provided in newly-built dwellings, but discrepancies between design and as-built performance have been widely reported, most notably regarding a performance gap between designed and as-built energy use (ZCH, 2014). For example, Johnston et al. (2015) found that the difference between predicted and measured as-built thermal performance was sometimes over 100% in the 25 dwellings they studied. Reasons for these discrepancies were attributed to modelling assumptions regarding party-wall bypass, thermal bridging and wind-washing, particularly where workmanship was poor. Additionally, assumptions used to characterise the performance of technologies in controlled conditions may not correspond to performance in real buildings; Bennett et al. (2019) found boilers were much less efficient in-situ compared to assumptions in performance standards. Performance targets may also have unintended consequences, for example Love et al. (2017) investigated air permeability lodgement results after testing became mandatory, they found unusual distributions in the air permeability measurements and suggest this could reflect builders making incremental improvements in airtightness until target air permeabilities are achieved. Love et al. suggest this could result in rapid degradation of air permeability after the testing is complete, thereby reducing energy performance and altering ventilation performance in the longer term. Such examples highlight the wide variety of issues potentially associated with performance gaps.

The Zero Carbon Hub (ZCH, 2016) found that there could also be a performance gap associated with the difference between actual performance of ventilation systems compared to design intent and regulatory requirements. ZCH (2016) investigated dwellings with mechanical ventilation with heat recovery (MVHR) and continuous mechanical extract ventilation (MEV) systems, they highlighted problems during the installation causing inappropriate or poorly functioning ventilation systems (for example inappropriate details such as duct lengths and locations), inadequate enforcement of the Building Regulations and commissioning procedures were also found to contribute to this performance gap. Much of the research investigating as-built ventilation systems has focused on MVHR, for example Foster et al. (2016), Sharpe et al. (2016), and Gupta et al. (2018), such studies have often found improperly balanced MVHR systems, evidence of poor installation of systems and occupants using the systems differently to the design intention.

MHCLG (2019b) states that the most common ventilation systems in newly built English dwellings were either background ventilation with intermittent extract (system 1 in ADF, often called natural ventilation) or continuous mechanical extract ventilation (system 3 in ADF). These two systems make use of similar technologies; mechanical extract fans and background ventilation (usually trickle vents). Crawley et al. (2019) found that 11% of the UK air permeability results lodged in the Air Tightness Testing and Measurement Association (ATTMA) database between 2015 and 2017 were of dwellings with continuous MEV and 62% were naturally ventilated. Although not all newly built dwellings are recorded in the ATTMA database, this gives an indication of the prevalence of newly built dwellings using such systems. Despite their prevalence in the UK, there are relatively few empirical studies in occupied homes designed to comply with ventilation system 1 or system 3 which investigate the ventilation equipment actually provided, how this equipment is used and the ventilation rates achieved.

Research investigating ventilation systems 1 or 3 has investigated whether the equipment provided in homes as-built matches ADF's description. MHCLG (2019b) found that only one of the 25 dwellings studied met the ADF fan flow rates and trickle vent provision, similarly ZCH (2016) found that flow rates through MEV systems in normal low flow conditions were lower than ADF requirements in all 6 dwellings studied. While not a representative sample, these findings suggest that ventilation rates in the wider stock may not be adequate in many cases.

Additionally, although it is a technical document, ADF includes assumptions regarding occupant use of the ventilation systems it describes. MHCLG (2019b) found that trickle vents had often been closed and mechanical ventilation systems switched off despite the assumption in ADF that these will be continually open and on respectively, ZCH (2016) found similar results in the homes they studied. Additionally, Sharpe et al. (2015) conducted structured interviews with 200 occupants of naturally ventilated dwellings with trickle vents in Scotland (where similar but different building regulations and guidance apply), and found that 63% reported having their trickle vents always closed, in contrast with the design assumption that they will be open. Since ventilation systems including mechanical extract fans and trickle vents are common in the UK dwelling stock, understanding their actual use by occupants is important. Occupants will take further actions which affect whether the ventilation rates they experience are adequate, such as window-use. It is challenging to characterise such actions; models often take the form of consistent actions in response to specific, predictable conditions, for example specific times of day (Underhill et al., 2020; Liao et al., 2019) or internal and external temperatures (Gilani and O'Brien, 2020). However, research investigating window use has found that occupants may not follow the patterns assumed by models (Fabi et al., 2012).

Finally, MHCLG (2019b) measured ventilation rates in 10 of the dwellings they studied and in 7 of these the ventilation rate was below the ADF recommended value, while ZCH (2016) found ventilation rates exceeding ADF requirements in 4 of the 5 dwellings with continuous MEV systems they studied (in spite of the low fan flow rates mentioned above). Sharpe et al. (2015) found ventilation rates were below commonly recommended values in 42% of the 40 naturally ventilated bedrooms they studied in Scotland. These examples have either used measurement techniques which provide average ventilation rates over minutes or hours and may be repeated to give a number of 'snap-shot' measurements (Sharpe et al., 2015; ZCH, 2016), or have used a technique which gives the average ventilation rate over several days (MHCLG, 2019b). Such methods give a useful indication of the ventilation in homes. However, there is very little published ventilation research investigating variation of ventilation over time. Wallace et al. (2002) measured a 70-minute average ventilation rate every 2-4 hours over a year in an occupied home, they found a mean ventilation rate of 0.56 ach with a standard deviation of 0.65 ach, showing that ventilation can be highly variable. Wallace et al.'s research may be unusual because methods to generate such results are expensive and invasive for occupants.

1.5 Structure of this thesis

The research presented in the sections above begins to suggest that ventilation equipment, its operation and ventilation rates as-built are not always in line with

ADF's description in homes with mechanical extract ventilation and trickle vents, however there has been relatively little work in this area despite their prevalence in the dwelling stock. Moreover, the variation in ventilation rates has rarely been investigated in occupied homes with such systems, and this may have significant implications regarding the interpretation of the adequacy of ventilation to meet the needs of the occupants. The gap in the literature relating to the ventilation achieved in occupied dwellings with these ventilation systems is at the heart of the research presented in this thesis, and will be explored further in Chapter 2.

Chapter 2 starts by presenting the physics of ventilation in buildings and goes on to review the literature relating to three main themes which are carried through the remainder of this thesis: ventilation measurement methods, variation of ventilation rates and occupant actions affecting ventilation rates.

Chapter 3 justifies the research approach and choice of methods used to address each of the sections of work. Detailed descriptions of each of the case study dwellings are also provided in this chapter.

Through the literature review in Chapter 2, it will become clear that existing ventilation measurement methods are not currently feasible for long term measurement campaigns in occupied homes without long-term temporal averaging of results. This work developed an existing method for measuring ventilation rates to facilitate measurements in occupied homes without long-term temporal averaging. The development and implementation of this method, its limitations and uncertainties are presented in Chapter 4.

In Chapter 5, the ventilation results from several case studies are presented. This chapter explores the variability of measured ventilation rates, with reference to changing weather conditions and changing configuration of the dwelling (including the use of doors, windows and trickle vents). These are expected to have significant impact on ventilation rates, but the literature review identifies limited research investigating this in occupied homes.

Through the literature review in Chapter 2 it is shown that much empirical work on ventilation provides only limited insights regarding the occupants of the buildings they study. Social Practice Theory (SPT) was used to explore occupants' ventilation-related actions, particularly by comparing the intended use of ventilation equipment set out in ADF to the participants' practices. The results of this comparison are presented in Chapter 6.

Finally, Chapter 7 provides a summary of the conclusions from each of the results chapters, highlights the implications and areas for future research. The complexities of ventilation in occupied homes identified through combining the results of each of the strands of research is also presented in a global discussion of the results, along with a reflection on the use of mixed-methods research in this thesis.

Chapter 2

Background Theory and Literature Review

In the previous chapter the link between ventilation and domestic energy use, indoor air quality and the health of building occupants was outlined. It was noted that the English Building Regulations require adequate ventilation in buildings and that the most common strategies for newly built dwellings include trickle vents and mechanical extract ventilation (MEV), but that there has been relatively little literature exploring ventilation in homes with these technologies.

In this chapter, the literature relating to measurements of ventilation in homes complying with past and present versions of Approved Document F (ADF) will be critically reviewed and a gap in the literature regarding the performance of ventilation systems in occupied homes over time will be identified. In order to do this the chapter will begin with a physical overview of ventilation and airtightness, before outlining the theory of the ADF ventilation systems. In order to critically assess the literature studying ventilation in occupied homes, the theory relating to measurement of ventilation in buildings will then be presented before returning to critically review the literature concerning measurement of ventilation in homes built to ADF designs. The review will then be expanded to consider technical measurements of ventilation in occupied homes more broadly. At this point, the sociotechnical character of homes and the influence of this on ventilation and its measurement will be considered. The extent to which the sociotechnical nature of ventilation in homes has been studied in research of ADF compliant homes and other studies of ventilation in homes will be reviewed, noting the limited published literature in this area. An introduction to social practice theory as a theoretical framework for analysing everyday actions will be given, and a review of the literature in which social practice theory has been applied to ventilation and other relevant practices. Finally, the conclusions of the chapter will set out the research questions this work seeks to address relating to the measurement and adequacy of ventilation in homes intended to be provided with ADF compliant ventilation systems.

2.1 Theory of ventilation and ventilation measurement in buildings

This section presents the physical theory relevant to ventilation in buildings, and to the ventilation strategies given in ADF. The physical drivers of ventilation are first explained, followed by the theory of air permeability and airtightness. Finally, the ventilation strategies given in ADF are discussed.

2.1.1 Physics of ventilation

Air flows from regions of high pressure to low pressure. Ventilation in buildings is driven by indoor-outdoor pressure differences caused by wind, temperature differences and mechanical ventilation where this is present. The airflow through an opening due to a pressure difference is often modelled as a power law (ASHRAE, 2017b):

$$Q = c(\Delta p)^n, \tag{2.1}$$

where Q is the airflow rate, c is the flow coefficient, Δp is the pressure difference across the opening and n is the flow exponent. The flow exponent varies between 0.5 for turbulent flow and 1 for laminar flow (Liddament, 1996).

The stack effect refers to the flow of air into and out of a building due to buoyancy. Stack pressure is the hydrostatic pressure caused by the force of gravity on the mass of a column of air. Since air of different temperature has different density, an indoor-outdoor temperature difference causes a difference in the stack

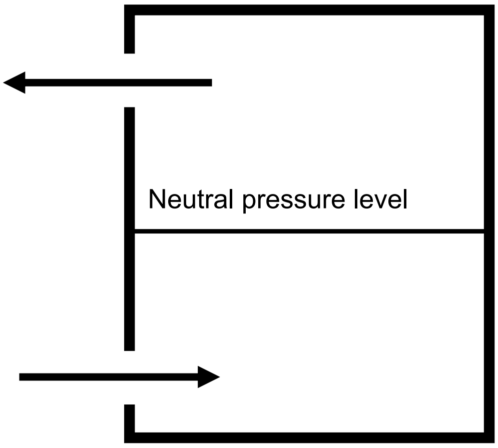


Figure 2.1: Pattern of air flow due to the stack effect in a heated building assuming no wind. Arrows represent the movement of air.

pressure between indoors and outdoors at a given height (ASHRAE, 2017b). For a single column of air where the temperature and barometric pressure are constant over the height of interest, the stack pressure is given by the following equation (ASHRAE, 2017b):

$$p_s = p_r - \rho g H, \tag{2.2}$$

where p_s is the stack pressure, p_r is the pressure at the reference height, ρ is the air density, g is the acceleration due to gravity and H is the height above the reference height.

Figure 2.1 shows a simplified pattern of air flow due to the stack effect, the building is warmer than its surroundings and this assumes no wind. Figure 2.1 shows that air enters the building near the bottom and leaves near the top, the neutral plane level (NPL) represents locations where there is no indoor-outdoor pressure difference. The location of the NPL is affected by the distribution of air leakage paths in the building envelope, with large openings near the bottom of the building shifting the NPL downwards and vice versa for large openings near the top of the building (ASHRAE, 2017b).

The pressure caused by wind may be estimated using the following equation (Hens, 2017):

$$p_w = C_p \rho U^2/2, \tag{2.3}$$

where p_w is the wind pressure relative to the outdoor pressure in an undisturbed flow, C_p is the wind surface pressure coefficient ρ is the outdoor air density and U is the wind speed.

This equation is derived from Bernoulli's law which gives the pressure drop when the velocity of wind drops from U to zero due to colliding with an infinite obstacle, the wind surface pressure coefficient accounts for the effect of colliding with a finite obstacle (Hens, 2017). This coefficient will be affected by wind direction, building geometry, local obstructions and the point on the façade under consideration. Most data on wind surface pressure coefficients are measured with the wind normal to the surface, although previous studies have developed trigonometric functions to convert C_p normal to the building to different incident wind angles (ASHRAE, 2017b). In urban environments wind is turbulent, strongly affected by the local topology and subject to instantaneous fluctuations in wind speed and direction (Gough et al., 2018), this makes calculation of wind-driven pressure differences challenging.

Unbalanced mechanical ventilation affects the internal pressure. Mechanical extract systems decrease internal pressure, which causes an increase in air flow from outdoors to indoors to 'make-up' the extracted air, whereas mechanical supply ventilation increases internal pressure such that internal air is forced to escape through the building fabric or planned infiltration openings (Liddament, 1996). In both cases, the ventilation is dominated by the mechanical system if the change in pressure induced by the mechanical system is significantly greater than that caused by wind and temperature (Liddament, 1996).

Where indoor pressures are not constant, analysis of ventilation is complicated by internal airflows. Internal pressure is affected by internal conditions including temperature differences within a building and the air leakage between different zones in the building (ASHRAE, 2017b).

Since ventilation is related to pressure difference via a power law, pressure differences arising from different sources must be combined rather than summing the air flows caused by each (ASHRAE, 2017b). In order to accurately model ventilation, this should be done separately for each air leakage path and planned ventilation opening in the building envelope since pressure differences are not uniform across the building envelope (e.g. stack and wind pressures vary with location on the building envelope). However, determining the size and location of all leakage paths in a building envelope is not currently possible and this is a significant source of uncertainty in modelling ventilation (Emmerich, 2001).

2.1.2 Airtightness and air permeability

The total ventilation in buildings is made up of ventilation deliberately provided through fans and vents and ventilation occurring as a result of unplanned and uncontrolled air leakage paths in the building envelope. Airtightness is a general term for describing the leakiness of a building fabric. Johnston et al. (2011) found that airtightness was affected by construction type, number of stories, complexity of the building design, site supervision and workmanship during the build.

Measurements of air permeability are used to quantify airtightness such that comparisons can be drawn between buildings. Air permeability is measured using a pressurisation test (also called a blower-door test), in which a fan is installed into the envelope of the building and the flow rate required to maintain a given pressure difference between indoors and outdoors is measured (ATTMA, 2016). Tests complying with ATTMA (2016) require measurements of flow rate at a minimum of seven different pressure differences across at least a 30 Pa range. These results are fitted to Equation 2.1 using a curve fitting technique (often a least squares algorithm) to give values for the flow coefficient and flow exponent. In order to compare the results of different buildings these values are used to give the flow rate expected at a pressure difference of 50 Pa, this result is normalised by the area of the building envelope to give the air permeability in $m^3/(m^2$ hr) at 50 Pa. Air permeability measurements are conducted with all planned ventilation closed or switched off, in order to quantify the unplanned leakiness of the building.

2.2 Measuring ventilation

Section 2.1.1 showed that ventilation in buildings is expected to be variable over time, as it is dependent on weather conditions, use of mechanical ventilation (MV) as well as occupant use of doors and windows. Also, it was shown that methods for modelling ventilation often make simplifying assumptions regarding air leakage paths and combinations of multiple driving forces. Moreover, Chapter 1 showed that concerns have been raised regarding the ventilation achieved in dwellings as-built compared to designed. Furthermore, Chapter 1 showed occupants spend a considerable amount of time at home and that the indoor air quality (affected by the ventilation rates) they experience at home have consequences for their health. These issues combine to suggest it is important to measure ventilation in homes as-built and as-occupied. The present section deals with the theory of different ventilation measurement methods. This allows the assumptions, limitations and advantages of these methods to be discussed in later sections when critiquing research on ventilation in homes.

The review that follows focuses on established ventilation measurement methods. There has been some recent work in developing novel methods for ventilation measurement, for example Carrilho et al. (2016) and Alavy et al. (2018) developed a signal processing method while Hormigos-Jimenez et al. (2017) used volatile organic compounds (VOC) concentrations to estimate ventilation rates. However, these methods have not been widely used and currently rely on established methods for verification. The following sections discuss the use of pressurisation tests to estimate annualised ventilation rates, CO_2 as a proxy for adequate ventilation and tracer gas methods.

2.2.1 Pressurisation tests

Pressurisation tests have been used to estimate ventilation rate using simple ratios. Most commonly the annualised ventilation rate is estimated as follows (Jones et al., 2016):

$$ACH = N_{50}/20, \tag{2.4}$$

where ACH is the annualised air change rate and $N_{50} = Q_{50}/V$, where N_{50} is air changes per hour at 50 Pa, Q_{50} is the volumetric flow rate at 50 Pa found using a pressurisation test, and V is the volume of the building.

Air permeability measurements are widely conducted in newly built dwellings, for example air permeability measurements have been compulsory for newly built UK dwellings since 2006 (Love et al., 2017). Air permeability measurements are therefore available for a large number of dwellings, meaning that the data required for the above equation is widely available and estimating ventilation rate in this way is relatively cheap and straightforward (Pasos et al., 2020). However, as mentioned above, air permeability measurements are conducted with all planned ventilation openings closed and all mechanical ventilation switched off. This may limit the representativeness of air permeability test conditions to occupied conditions.

Additionally, there are concerns about the validity of the above estimation. Different numerators and denominators have been used; Sherman (1987) states that the annualised whole dwelling ventilation rate often is assumed to be given by Equation 2.4, but argues that dependent on local weather conditions, building height and leakage type the denominator could vary between 10 and 30. In the UK, the Standard Assessment Procedure (SAP) – a method for estimating the energy efficiency of a building – uses air permeability rather than the air change at 50 Pa as the numerator to estimate the ventilation rate due to infiltration (unplanned ventilation) (BRE, 2014).

Sherman (1998) stresses the limitations of approximating ventilation using Equation 2.4 given variations in weather conditions and dwelling characteristics. Liddament (1996) suggests that this relationship is particularly inaccurate for naturally ventilated buildings as the instantaneous ventilation rate can deviate significantly from the average. Furthermore, Jones et al. (2016) present a history of these ratios and find that the original source of the relationship is likely empirical, but the original source could not be identified and several different datasets have been implicated over the years. While this method may provide a quick and easy estimation of ventilation, the result is extremely uncertain.

2.2.2 CO_2 as a proxy for ventilation

Observation of CO_2 concentration above 1000 ppm has been used as an indication of inadequate IAQ and therefore inadequate ventilation (Persily, 1997). This is not a quantitative measurement of ventilation, but has frequently been used as an indicator of adequacy of ventilation, for example Ridley et al. (2013), Sharpe et al. (2014), and McGill et al. (2015). Persily (1997) finds that this rule of thumb originated from work finding 80% of unadapted people find the body odour in a space acceptable if the ventilation rate is sufficient to limit the CO_2 concentration to 700 ppm above the outdoor concentration.

Persily (1997) argues that the absolute CO_2 concentration should be used cautiously as an indicator of poor ventilation or IAQ. Reaching the threshold of 1000 ppm is strongly influenced by the size of the space of interest and the number of people present. This method is unable to indicate the presence of pollutants which are not associated with occupancy, such as emissions from building fixtures or the ingress of outdoor pollutants. Moreover, this method cannot indicate inadequate ventilation in the space unless people are present for a minimum amount of time (which is dependent on the number of occupants, ventilation rate and size of the space). A CO_2 concentration below 1000 ppm is not a sufficient condition for adequate IAQ or ventilation.

2.2.3 Tracer gas method for ventilation measurement

The two sections above outlined simple methods which have been used to give approximate indications of ventilation in buildings. However, tracer gas techniques are the most widely used for ventilation measurement (Cui et al., 2015). This section will first outline the underlying theory of all tracer gas methods and the assumptions the analysis is based on. The required characteristics of tracer gases will then be discussed, referring to the most common gases. The interpretation, accuracy and practicality of the most common experimental configurations will then be discussed.

2.2.3.1 Premise and assumptions of the technique

In tracer gas methods a specific gas is used to 'tag' the airflow in a volume of air. The analysis is based on the continuity equation which states that (Penman and Rashid, 1982):

$$Q = \sum_{i=0}^{N} V_i, \tag{2.5}$$

where Q is the total flow volume leaving the space and V_i is is the volume of flow into the space from outdoors ($i = 0$) and from the i^{th} connected space.

By considering the injection rate of tracer gas in the measured zone and concentration of the tracer gas in each zone, the continuity equation can then be expressed in the following terms (Penman and Rashid, 1982):

$$V\frac{dC}{dt} + QC = Q_T + \sum_{i=0}^{N} C_i V_i, \tag{2.6}$$

where V is the effective volume of the measured zone, C is the concentration of the tracer gas in the measured zone, Q_T is the volumetric rate of injection of the tracer gas into the measured zone, C_i is the concentration of the tracer gas in the i^{th} connected zone, and V_i is the volumetric flow of air into the zone being measured from of the i^{th} connected zone.

A separate tracer gas must be used for each connected zone if the above equation is to be constrained. In this case, Equation 2.6 must be formulated as a matrix, where each row in the concentration and source strength matrices relates to each zone, and each column represents a tracer gas. There some examples in the literature of this kind of analysis, for example Smith (1988), Harrje et al. (1990), and Liu et al. (2018). However, the experimental set-up is complex for this technique, for example requiring specialist equipment to dose and measure multiple tracer gases in multiple zones, this limits the practicality of utilising this method. The simplifying assumption that the space can be represented as a single zone is much more common than multi-zone analysis, single zone analysis will be be explored further here.

Under the single zone assumption, Equation 2.6 reduces to (Sherman, 1990):

$$V\frac{dC}{dt} + QC = Q_T. \tag{2.7}$$

The derivation of the above equations require the assumption that air is well mixed within measurement zones and therefore that the tracer gas is homogenously distributed, and the single zone assumption requires that air is exchanged only between the measurement zone and outdoors. Guidance from technical bodies (BSI, 2017; ASTM, 2018; ASTM, 2011) will be consulted along with examples from the literature in discussing the above assumptions in the context of field experiments in a building.

A single zone is defined as ‘a set of spaces wherein the concentration of a tracer gas is maintained uniformly throughout and that only exchanges air with the outside’ ASTM (2011, p. 2). This guidance goes on to acknowledge that single zones within larger buildings are hard to isolate. ASTM (2011) recommends that the tracer gas concentration at representative locations of a zone should differ by less than 10%, exactly what constitutes a representative location ‘depends on foreseeable problems with the tracer gas distribution’ (ASTM, 2011, p. 10). The guidance suggests measurements should be taken at mid-level between floor and ceiling, if the zone is made up of more than one room then all rooms should be measured and undifferentiated open space should be measured at three locations.

The single zone approximation has been applied over different spatial scales in the literature. Wallace et al. (2002) released and measured tracer gas in different areas of the dwelling and took the whole dwelling as a single zone, and used fans to mix the air and achieve homogeneity of the tracer gas. Guo and Lewis (2007) noted the difficulty in obtaining homogeneity of tracer gas throughout the dwelling and instead measured tracer gas concentration in bedrooms with the door closed assuming that the ventilation rate calculated using this data represented the ventilation rate of the whole dwelling. However, since airflow between the bedroom and the rest of the dwelling is possible, the calculated rate instead reflects the effective ventilation rate: the ventilation rate that would produce the tracer gas concentrations observed if there was only air exchange with outdoors (Roulet, 2008; Mumovic et al., 2009).

The effective ventilation rate is systematically biased as it neglects the flow between the measured space and the rest of the building.

Cui et al. (2015) and Van Buggenhout et al. (2009) studied the effect of sensor location and imperfect mixing in tracer gas experiments. They conducted experiments in test chambers with a reference air exchange value measured through extract fans. Both studies concluded that where possible placing sensors at an air outlet is the most accurate location for a single sensor. Cui et al. (2015) found deadzones where air does not mix well in corners and concluded these are best avoided for sensor placement. Van Buggenhout et al. (2009) found a maximum difference between the reference ventilation rate and measured ventilation rate of 86% due to sensor placement, although this study was conducted in the context of ventilation of livestock barns and ventilation rates between 9 h^{-1} (air changes per hour) and 27 h^{-1} was tested - far higher than in typical domestic settings.

Research in naturally ventilated buildings cannot be compared to another reference airflow measurement and in dwellings sensor placement may be complicated by the arrangement of the home. It is not always clear how the issue of sensor placement and homogeneity is addressed in domestic ventilation research. Howard-Reed et al. (2002) state that they followed the ASTM guidance, but give no details of their sensor placement when testing the uniformity condition. Bornehag et al. (2005) refer to guidance from Nordtest (1997) which recommends ensuring constant emission of tracer gas per unit volume and that the tracer gas measurement point is in a ‘representative’ location more than 1m from the source. Iwashita and Akasaka (1997) and Guo and Lewis (2007) placed sensors centrally in each room that they measured. Stymne et al. (1994) placed sensors as close to any identifiable exhaust as possible in kitchens but gave little indication of where sensors were placed in other rooms. In all of the above cases the spatial homogeneity of the tracer gas is unknown.

In cases where the homogeneity condition is not met, ASTM (2011) and BSI (2017) guidance suggests using fans to facilitate well mixed air. This approach was taken by Wallace et al. (2002), Crump et al. (2005), and Iwashita and Akasaka

(1997) in their tracer gas experiments. However, altering the physical conditions in this way means that the conditions measured are not the same as those experienced in dwellings under normal living conditions. BSI (2017) state that mixing fans should not be used if there is significant temperature stratification as fans would affect the ventilation caused by the stack effect, and fans should be avoided if they are likely to impinge on leakage areas and thus affect ventilation by causing pressure differences. Additionally, Liddament (1996) argues that fans should not be used if the aim of the measurement is to understand air quality, because areas of poor mixing are important in this context.

Finally, it should be noted that the above equations refer to the effective volume of the zone - the volume of the zone which takes part in air exchange. This is often assumed to be the physical volume of the zone, however if there are significant 'dead spaces' (where air does not mix) this can cause inaccuracies in the inferred ventilation rates (Liddament, 1996). This is not usually discussed in tracer gas measurements of ventilation in buildings, but Sherman (1990) suggests that the effective volume of a zone is rarely known to better than 20% due to the possibility of unknown dead-zones.

The application of other aspects of the other assumptions involved in tracer gas methods are more specific to the particular experimental configuration. These will be discussed after the required characteristics of tracer gases are discussed in the following section.

2.2.3.2 Choice of tracer gas

The most commonly used tracer gases are SF_6, CO_2 and PFTs (perflourocarbon tracers). According to Cui et al. (2015) an ideal tracer gas should have the following properties:

1. Safe (non-toxic, non-allergic, non-flammable)
2. Non-reactive (it should not react chemically or physically with the environment)
3. Easily measurable

4. Miscible with air (similar density)
5. Distinguishable from the constituents of air

However, no tracer gas perfectly fulfils all of these criteria. Both SF_6 and PFTs are denser than air which means that the way they flow is not necessarily representative of the bulk airflow in the space, the influence of this on the measured airflow rate is unclear (Cui et al., 2015). Guo and Lewis (2007) used the decay technique with both metabolic CO_2 and SF_6 tracer gases and found agreement usually within 0.1 h^{-1}, but up to 0.3 h^{-1} although possible reasons for the discrepancies were not a focus of the paper.

There are environmental concerns about SF_6 and PFTs. SF_6 has a 100-year global warming potential (GWP) of 22,800; the GWP is a measure of the integrated radiative forcing over a specified time period, relative to CO_2 which has a GWP of one (Solomon et al., 2007). In the EU the use of SF_6 now falls under EU Regulation No 517/2014 (2014) governing the use of flourinated greenhouse gases. As a result it is no longer feasilbe to use SF_6 in tracer gas experiments in the EU. The GWP of PFTs has not been fully assessed but may be assumed to be similar to other perfluoro compounds which typically have 100-year GWPs in the region of 10,000 (Watson and Sullivan, 2012).

CO_2 is has several desirable qualities. CO_2 sensors are cheaper and more easily accessible than other types of tracer gas sensors (Roulet and Foradini, 2002). CO_2 is naturally present in the atmosphere so may be more acceptable to occupants and therefore facilitate longer measurement campaigns than other tracer gases (Penman, 1980). The 8-hour exposure limit for CO_2 is 5000 ppm, and the 15-minute exposure limit is 30 000 ppm (Persily, 1997) - these concentrations are beyond the levels necessary for ventilation measurements. Also, CO_2 has a density similar to air (Cui et al., 2015). However, unlike SF_6 and PFTs, CO_2 is naturally present in the atmosphere so the background concentration must be accounted for in analysis (ASTM, 2018). There are also several sources of CO_2 in dwellings, including respiration and burning fuel.

Metabolic CO_2 (a product of respiration) can be directly used as a tracer gas, first demonstrated by Penman (1980) in an investigation of the ventilation rate in a university library. This can be advantageous in that it removes the need for the introduction of gases which would not naturally be present in the atmosphere, making the measurement technique cheaper and reducing its environmental impact. However, when using CO_2 as a tracer gas the presence of occupants must be accounted for to avoid systematic uncertainties related to the presence of an unaccounted source of the tracer gas.

2.2.3.3 Tracer gas experimental configurations

There are several tracer gas experimental methods, the three most common will be discussed here with reference to the advantages and disadvantages of each. Passive ventilation measurement methods tending to make use of PFTs, will be discussed first. This is followed by a discussion of the concentration decay method, the most popular configuration, most often making use of SF_6 or CO_2. Finally two constant concentration methods will be presented: using assumed constant emission of metabolic CO_2 for equilibrium analysis and using a controlled feedback system.

2.2.3.3.1 Passive tracer methods. This technique makes use of averaging over time, and is usually carried out using PFTs. A PFT source will emit while a diffusion tube absorbs this gas over a period of time. The samplers are commonly diffusion tubes, these tubes are open at one end and filled with a gas adsorbent, such as activated carbon. Depending on the exact experimental design either the PFT is emitted at a constant rate (as Stymne et al. (1994)), or emitted at a rate dependent on the ambient temperature (as Liddament (1996)).

The continuity equation is averaged over time to give (Liddament, 1996):

$$V\overline{\left(\frac{1}{Q}\frac{dC}{dt}\right)} + (\overline{C}) = \overline{\left(\frac{Q_T}{Q}\right)}, \tag{2.8}$$

where the bars show that the terms are averaged over time. The first term in this equation tends towards zero if $(1/Q)$ is small compared to the measurement time, and if the emission rate is constant then:

$$\overline{1/Q} = \overline{C}/Q_T. \tag{2.9}$$

From this the inference is often made that:

$$\overline{Q} = Q_T/\overline{C}. \tag{2.10}$$

However, this step is only valid if the air change rate is constant throughout the measurement period because in general the average of the inverse is not the same as the inverse of the average.

Examples of measurement time for passive tracer techniques vary considerably in the literature, from two days (Bornehag et al., 2005) to a month (Bekö et al., 2016). As discussed in Section 2.1 weather conditions and use of doors, windows or variable mechanical ventilation by occupants will affect the ventilation rate and the validity of the constant ventilation rate assumption. Sherman (1990) argues that it is not clear what a measurement of this type means if the ventilation rate is not constant throughout the measurement period.

This method can usefully be applied to give an idea of the ventilation conditions, and may be accurately applied if the ventilation is not expected to be variable, for example in airtight buildings where ventilation is dominated by continuous mechanical ventilation (Liddament, 1996). However, this method is unable to represent peaks in ventilation rates due to window opening or weather conditions. Sherman (1989) quantified the seasonal under-prediction of air change rate from applying this equation when the air change rate is not constant to be in the range 20-30%. Bekö et al. (2016) used several ventilation measurement techniques to explore ventilation rates in five occupied dwellings in Copenhagen. They applied passive tracer measurements over one month and over five days as well as using the constant concentration method (discussed in Section 2.2.3.3.5) to calculate ventilation rates every 3-4 minutes over 2-4 days (coinciding with the 5-day PFT measurements) and they repeated these measurements several times over a year. Bekö et al. found that the passive tracer techniques applied over both time scales reflected broad overall differences between the dwellings they studied (for example, which dwelling usually had the highest ventilation rate), but that the method with greater time resolution identified higher ventilation rates during occupied daytime periods than during unoccupied or night-time periods. Bekö et al. argue that pollution sources (for example moisture generation) will also be variable over daily periods so this scale of variation in ventilation rates is important to the conditions that the occupants experience.

2.2.3.3.2 Concentration decay. In this method the tracer gas is distributed in the volume of the zone, the source is then removed or switched off and the tracer gas is allowed to decay towards the outdoor concentration, this decay period is used to determine the air change rate.

Since the decay period is used for analysis, the tracer source term in Equation 2.7 is set to zero and the differential equation is solved by (Liddament, 1996):

$$C(t) = C_0 \exp(-At), \tag{2.11}$$

where A is the air change rate ($A = Q/V$), C_0 is the concentration at $t = 0$. Where CO_2 is used as the tracer gas, the concentration values in the above equations are replaced by the concentration difference between indoors and outdoors since CO_2 is naturally present in the atmosphere (ASTM, 2018).

Equation 2.11 is used to fit a series of concentration measurements taken during the decay period to give the air change rate parameter (Equation 2.11 is usually linearised by taking the natural logarithm and a linear regression used to estimate the air change rate). The air change rate is therefore assumed to be constant over the period in which the concentration measurements are used to fit the model. ASTM (2011) recommend that at least five measurements of concentration should be taken for each measurement of ventilation rate. The frequency of concentration measurements is variable in the published literature, from seconds (Cui et al., 2015) to half an hour (Crump et al., 2005), and measurement periods range from 10 minutes (Cui et al., 2015) to eight hours (Parsons, 2014). These periods are much shorter than typical passive tracer measurements. According to Etheridge and Sandberg (1996) wind speeds and pressures averaged over approximately an hour may be considered constant for the purposes of analysing ventilation driving forces. However, Potter (1979) note that wind fluctuates on small time scales, so instantaneous measurements of wind can be very different to averaged values, and this can have a significant impact on ventilation rates.

The identification of appropriate periods of concentration data for decay analysis is not usually discussed in the literature. Cui et al. (2015) conducted their study in an experimental chamber and found that the beginning of the decay often did not fit with the rest of the exponential decay, so they waited for the concentration to reach an arbitrary level and assumed that the flow paths were stable and there was reasonable mixing after this initial period. Wallace et al. (2002) waited for 30 minutes after injecting SF_6 before beginning decay analysis, with fans running to encourage mixing throughout the settling and measurement period. Roulet and Foradini (2002) and Guo and Lewis (2007) acknowledged that the decay periods are unclear and manually identified regions for analysis in their studies using metabolic CO_2. In general, concerns over good mixing and the emergence of stable airflows in the initial period of the decay drive a tendency to wait for a period of time before beginning the decay analysis. However, the conditions required before beginning analysis are often unclear and lack clear justification.

Metabolic CO_2 is built up by the presence of occupants and the decay that results when the space becomes unoccupied can be used to calculate the ventilation rate (ASTM, 2018). If occupants or any other source of CO_2 were present and unaccounted for this would result in an erroneously low calculated air change rate. Almeida et al. (2020) measured ventilation rates in two rooms of an occupied dwelling using the metabolic CO_2 decay method, they note that the presence of occupants in other rooms of the dwelling which were not measured resulted in lower calculated ventilation rates during these periods. Although the CO_2 concentration decayed in the measured rooms during these periods, the inhomogeneity of CO_2 throughout the dwelling resulted in skewed results. This highlights the requirement for the whole dwelling to be unoccupied during measurement periods and the importance of homogeneity throughout the measured space.

Generally, there is little information in the metabolic CO_2 tracer gas literature on how unoccupied periods are identified. Guo and Lewis (2007) suggest that the difficulty in accurately determining when a dwelling is occupied is one of the reasons that there are few examples in the literature of metabolic CO_2 being used as a tracer gas. In this study decay periods were described as 'easy to distinguish' (Guo and Lewis, 2007, p. 240) and the occupants were asked to record a daily log-sheet. Presumably the logsheet was used to confirm that the decay periods were during unoccupied periods, but this corroboration is not discussed. Roulet and Foradini (2002) monitored a single office-room and manually identified periods of decaying CO_2, implying that prolonged periods of decreasing CO_2 can be interpreted as unoccupied periods. Other authors have used fixed hours of the day based on occupant reported daily habits (Bekö et al., 2010; Sharpe et al., 2015). This is subject to uncertainty given the variability of occupants' daily lives.

Many studies have attempted to determine the occupancy of an indoor space for reasons other than tracer gas experiments; the presence of occupants has a significant impact on the energy use of buildings, from the use of HVAC (heating, ventilation and air conditioning) to use of lighting and appliances (Chen et al., 2018). A broader review of this literature is presented in Section 3.2.3, discussing the method used to develop an algorithm for determining occupancy in this work. Here it is only noted that examples of metabolic CO_2 decay in the literature do not robustly investigate occupancy and either make assumptions based on time of day or manually identify unoccupied periods which would be extremely time consuming and lack repeatability for large datasets.

The requirement for an unoccupied zone where CO_2 is used means that the ventilation rate is not measured under the exact conditions in which the occupants inhabit the space. If the experiment does not take place with the same conditions as are present while they inhabit it, then the applicability of the measured rate to the conditions experienced will not be known. In this sense, measurements using SF_6 are advantageous in that they can take place during periods that the occupants are present.

2.2.3.3.3 Equilibrium analysis. Equilibrium analysis is a special case in which the injection rate is held constant until the concentration of the tracer gas reaches equilibrium. The ventilation rate must be constant for equilibrium to be reached and in this case the ventilation rate can be found using the following equation:

$$Q = Q_T / (C_{in,eq} - C_{out}), \tag{2.12}$$

where $C_{in,eq}$ is the indoor equilibrium concentration of the tracer gas, and C_{out} is the outdoor concentration of the tracer gas.

ASTM (2011) recommend that equilibrium can be considered to be met if the following inequality holds:

$$|\frac{C_{final} - C_{initial}}{T_{test}}| < 0.05 \frac{Q_T}{V_{zone}}, \tag{2.13}$$

where C_{final} is the final concentration of the tracer gas, $C_{initial}$ is the initial concentration of the tracer gas, T_{test} is the length of the time period over which equilibrium conditions are being tested and V_{zone} is the effective volume of the zone being measured. Again, where CO_2 is the tracer the concentration variables are replaced by the difference between indoor and outdoor concentrations of CO_2.

However, defining when equilibrium conditions have been reached is not described in any of the literature identified for this review. Mumovic et al. (2009) state that equilibrium conditions were rarely reached in their study of classrooms and they therefore more frequently used the build-up or decay of metabolic CO_2 to calculate the ventilation rate. Bekö et al. (2010) studied ventilation rates in bedrooms and used equilibrium conditions only when the build-up or decay of tracer was not appropriate and stated that only the most ‘trustworthy’ sections of the data were used. However, the way in which these were determined was not clarified.

The equilibrium technique has been used in occupied bedrooms where the injection rate is the CO_2 generation rate of the bedroom occupants. Guo and Lewis (2007), Sharpe et al. (2014), and Sharpe et al. (2015) all use this technique in occupied bedrooms using overnight data, making the assumption that CO_2 generation rates and ventilation rates are constant overnight, and that CO_2 generation rates can be approximated from tabulated values. The use of these tabulated values will briefly be discussed since it is shown to be a source of significant uncertainty.

Persily and Jonge (2017) states that a person's CO_2 generation rate can be found using the following empirical formula:

$$V_{CO_2} = RQ.V_{O_2} = \frac{0.00276 A_D M}{0.23 RQ + 0.77}, \tag{2.14}$$

where V_{CO_2} is the rate of carbon dioxide production in L/s, RQ is the ratio of the volumetric rate at which CO_2 is produced to the rate at which O_2 is consumed, known as the respiratory quotient, V_{O_2} is the rate of oxygen consuption in L/s, A_D is the du Bois surface area of the person which is related via an empirical equation to their height and weight, and M is the metabolic rate per unit of surface area measured in units of met (1 met = 58.2 W/m^2).

Examples from the literature often state the CO_2 generation rate used without reference to any of the parameters in Equation 2.14 except the metabolic rate of the people, for example Penman (1980), Roulet and Foradini (2002), Guo and Lewis (2007), Bekö et al. (2010), and Sharpe et al. (2015). The metabolic rate used usually comes from either ASHRAE or BS EN ISO 8996 (1990) cited either directly or though several steps.

ASHRAE (2017a) gives a table containing the metabolic rates associated with a wide variety of activities. This table cites three sources: Buskirk (1960), the 1964 edition of Parker and West (1973), and Passmore and Durnin (1967). While it was not possible to obtain the 1964 edition of Parker and West's bioastronautics data book or the Passmore and Durnin book, Buskirk (1960) states that factors such as age, fitness, time since eating, foods eaten and illness affect metabolic rate. Measurements of the same individual on different days can also be significantly different. Buskirk also suggests that adequately classifying different levels of physical activity and classifying different kinds of people into appropriate groups so that individuals can be fairly compared is not straightforward. It is also worth noting that many of the studies on metabolic rate involved military personnel who will have considerably different fitness levels compared to ‘ordinary’ people. Although Parker and West (1973) is a later edition than the one cited by ASHRAE, this data book states that the variation in metabolic rates between subjects can be 60%, or 30% when size is taken into account. For individuals, repeat measurements of the same activity can vary 10-15% day-to-day. Additionally, this data book relates to the metabolic rates of astronauts who will again have significantly different fitness levels than ordinary people.

BS EN ISO 8996 (1990) gives an even wider variety of activities and their associated metabolic rates. The standard does not refer to the original studies which found the values given. However, it does state that using tables to estimate an individual’s metabolic rate based on their generic kind activity is subject to ‘great uncertainty’, and that using tables for a specific activity or using an individual’s heart rate to estimate the metabolic rate would be subject to uncertainty of about 15%, although ASHRAE (2017a) states that using heart rate is a weak indicator of metabolic rate and should not be used where great accuracy is required. Smith (1988) used metabolic CO_2 as a tracer gas and measured the average height and the heart rates of the adults and children in the school that he studied, and then used this to estimate their metabolic rate. This level of detail in calculating metabolic rate is unusual in the ventilation literature.

Persily and Jonge (2017) published an updated table of activities and metabolic rates based on more recent data from the World Health Organisation and the Food and Agriculture Organisation of the United Nations. A subsequent version of the ASTM guidance (ASTM, 2018) emphasises the need to take into account the individual characteristics in terms of age, size and sex. As noted above, parameters other than metabolic rate in Equation 2.14 are not usually discussed. A 70 kg, 1.73 m man has a du Bois surface area of 1.8 m^2 ASHRAE (2017a), while CIBSE (2015) state that this is the normal surface area for a person. Sharpe et al. (2015) and Persily (1997) both use this value in their studies, but other papers do not explicitly mention the measured or assumed surface area of the people in their studies. The du

Bois surface area is an estimate of the surface area of the body based on the height and weight of the individual. Clearly not all participants in the above studies will have been 70 kg and 1.73 m. Finally, ASTM (2018) make clear that the respiratory quotient depends on the person's activity level, diet and physical condition. None of the studies identified for this review which used an estimate for the CO_2 production rate of the participants discuss this parameter, although this may change in the future given the clarification in newer guidance.

2.2.3.3.4 Tracer gas build up. The build-up of tracer gas concentration when the tracer gas is injected at a known rate is used to estimate the ventilation rate in this method. This has been applied with metabolic CO_2, first by Penman (1980) in a university library, this carries similar issues regarding the occupant CO_2 generation rate as discussed above.

2.2.3.3.5 Constant concentration. In this method a feedback loop is used to hold the concentration of the tracer gas in the measured space constant by varying the injection rate (ASTM, 2011), the ventilation rate is then calculated from the rate of injection of tracer gas required to keep the concentration constant at each time step. This is a general case of the equilibrium method discussed above, in this case the analysis does not assume that the ventilation rate is constant over the measurement period. By placing injection and control units in different parts of a building, interzonal flows can be accounted for such that the measurement specifically returns the indoor-outdoor ventilation rate. This method has been used to measure short-term variations in the ventilation rate, for example Bekö et al. (2016) used this method to measure the ventilation rate every 3 to 4 minutes over 2 to 5 days, but this requires sophisticated measurement and control equipment and is infrequently reported in the literature.

2.2.4 Summary of ventilation measurement methods

This section has discussed the theoretical basis of a range of the most common ventilation measurement methods. Examples of their use in the literature have been discussed with reference to the theoretical foundations of the methods and the treatment of assumptions inherent to the methods. Having seen that ventilation is driven

Table 2.1: Ventilation systems described in ADF (HMG, 2013b).

System number	System name
1	Background ventilators and intermittent extract fans
2	Passive stack ventilation (PSV)
3	Continuous mechanical extract (MEV)
4	Continuous mechanical supply and extract with heat recovery (MVHR)

by (constantly changing) weather, a particular theme has been the treatment of the variability of ventilation and the period over which ventilation rate (or other parameters) are assumed to be constant. This theme will continue to be followed through the later discussion of research addressing the adequacy of ventilation in homes built according to ventilation guidance.

The following section will discuss the strategy for ventilation laid out in Approved Document F to the Building Regulations. This will refer to the physical basis of ventilation introduced in Section 2.1. The research used to support revisions of the Approved Documents will also be discussed, with reference to the ventilation measurement methods discussed in the present section.

2.3 Ventilation in ADF compliant dwellings

As discussed in the introduction, UK building regulations require 'adequate means of ventilation provided for the people in the building' (HMG, 2010d). The current edition of Approved Document F to the Building Regulations (HMG, 2013b) sets out four systems which are assumed to meet this requirement of the Building Regulations, these are shown in Table 2.1. Chapter 1 noted that a high proportion of newly built homes have background ventilators with intermittent extract (system 1 in ADF) and continuous mechanical extract ventilation (MEV) systems (system 3 in ADF), but relatively little research has investigated as-occupied ventilation in homes with these ventilation systems. This section will review the current form of ADF regarding ventilation systems 1 and 3 and how requirements for these systems have changed over time based on previous research.

The overall strategy for ventilation set out in ADF splits ventilation into three components: extract ventilation, whole building ventilation and purge ventilation, with minimum ventilation rates given for each aspect (HMG, 2013b). Extract ventilation may be continuous or intermittent and is intended to remove pollutants at source to minimise their spread into the rest of the building. Minimum extract rates are room and location dependent which is intended to account for probable source strengths. Whole building ventilation is a nominally continuous air exchange intended to remove residual pollutants not removed by extract ventilation, and to remove other pollutants and water vapour produced throughout the building. Whole building ventilation rates are dependent on expected occupancy and floor area. Purge ventilation should be intermittent and available throughout the building and is intended to remove high concentrations of occasional pollutants or water vapour (e.g. painting and decorating, or smoke from burnt foods), this rate is uniform across all dwellings and may be provided through open windows. Windows are not used in provision of the first two types of ventilation. The following two sections will give further detail on the development of natural ventilation and mechanical extract ventilation.

2.3.1 System 1 - natural ventilation with intermittent MEV

Ventilation system 1 relies on natural ventilation for background ventilation, intermittent mechanical extract ventilators for extract ventilation and windows for purge ventilation. Background ventilation is provided through the building fabric and controlled background ventilators, often trickle vents. As seen from Section 2.1, in the absence of mechanical fans, weather and temperature drive ventilation, so the background ventilation will vary depending on the conditions. This was the only system included in the 1995 edition of ADF (HMG, 2000). Since then, required extract flow rates have not changed but the required area of background ventilation has increased with new editions of ADF.

Revisions to ADF in 2006 (HMG, 2006) were supported by research carried out by Crump et al. (2005) for the Building Research Establishment. Crump et al. (2005) studied 37 occupied dwellings and carried out measurement campaigns in summer and winter using the passive tracer method over two weeks in each season. They recorded a mean air change rate of 0.44 ach across the 37 dwellings (standard deviation = 0.11 ach) during the winter monitoring period, with the measured ventilation rate lower than the 0.5 ach recommended by BRE to avoid condensation in 68% of the dwellings. This study found that trickle vents were fully open in only 4 of the dwellings (it is not clear whether this was variable over the year), the high proportion of closed vents potentially contributed to the inadequate ventilation rates observed. The authors conclude that further research should examine the use of trickle vents and fans in dwellings, although this was 15 years ago there seems to have been little research exploring this. The mean ventilation rate increased to 0.62 ach with standard deviation of 0.23 ach in the summer, Crump et al. suggest that increased use of windows by the occupants contributed to this increase. However as discussed in the previous section, the passive tracer technique returns an average air change rate so the effect of changes in ventilation conditions during the measurement period cannot be disaggregated. This means that the extent to which the higher ventilation rate in summer is attributable to window opening cannot be explored. Additionally, regardless of season, ADF considers the whole dwelling ventilation rate separately from purge and extract ventilation so it is not clear how the average ventilation rate measured in each season relates to each component.

Alongside the findings of Crump et al. (2005), revisions to Approved Document L in 2002 had encouraged increasing levels of airtightness in newly built dwellings. This decreases the uncontrolled ventilation through the fabric of the building so trickle ventilation was increased to ensure that this did not leave dwellings with inadequate ventilation (ODPM, 2006). Additionally, ADF 2006 and subsequent versions of ADF make clear that the area quoted for background ventilation is the equivalent area rather than geometric area. The equivalent area is the area of a sharp-edged, circular orifice which would deliver the same volume flow rate of air under the same pressure difference as the opening being considered (HMG, 2006). Different trickle vents have different flow characteristics so using the equivalent area means that the same ventilation rate should be achieved regardless of the type of vent used.

Subsequently, DCLG (2010) reported research on the adequacy of ventilation in homes complying to 2006 standards in order to support the 2010 edition of ADF (HMG, 2010b) and 2013 amendments (HMG, 2013b). Similar to the previous study, 60% of the trickle vents were closed, all trickle vents were closed in 6 of the 22 dwellings investigated and all trickle vents were open only in 2 dwellings (between March and mid-May). Dwellings in this study were often equipped with less trickle ventilation than stipulated in the 2006 ADF, both as labelled and when measured using pressurisation tests with trickle vents opened and closed. Again the PFT method was used to measure ventilation, this time over a week, in 22 occupied homes. The occupants were asked to keep windows closed, to keep trickle vents open, to use bathroom fans on all bathing occasions and to use the kitchen extract at full speed during cooking. DCLG (2010) note that the ventilation rates observed in this sample are therefore likely to be higher than usual since occupants do not always use trickle vents and fans in this way. Even so, the majority of ventilation rates were below 0.5 ach, with flats recording a mean of 0.28 ach. In response to the low ventilation rates and inadequate area of trickle ventilation observed, the 2010 edition of ADF (HMG, 2013b) increased the required area of trickle ventilation when dwellings are expected to have an air permeability less than 5 $m^3h^{-1}m^{-2}$ at 50 Pa; the increased in equivalent area ranged between 5000 mm^2 and 20000 mm^2 depending on the floor area and number of bedrooms, a relative increase of between 15% and 40%. The wording of the passage relating to trickle vents and control of ventilation was changed from ‘Trickle ventilators are normally left open in occupied rooms in dwellings’ (HMG, 2006)[p 7] to ‘Trickle ventilators are intended to be normally left open in occupied rooms in dwellings’ (HMG, 2013b)[p 15]. This change of wording reflects the repeated finding that trickle vents are often closed in practice, but this was not apparently accompanied by any attempt to increase the proportion of open trickle vents (for example, by requiring improved instructions, improved labelling or non-closable vents).

MHCLG (2019b) report on research in homes built under the 2010 edition of

ADF. Again trickle vents were frequently closed, on average 3 in 10 trickle vents were closed in the sample of 80 homes (made up of system 1 and 3 dwellings). However, a survey of the participants found that 86% of the occupants broadly understood the purpose of the trickle vents and opened them ‘as needed’, as opposed to the stated intention in ADF that they are continuously open. The survey results showed that some participants opened the trickle vents in the summer and closed them in the winter; it is not clear what time of year the results regarding the proportion of open trickle vents were gathered. Additionally, the area of trickle ventilation was again different to the areas recommended in the 2010 edition of ADF.

Despite the requirement, in place since 2010 (HMG, 2010e), for fan flow measurements to take place at commissioning of the ventilation system, the majority of extract fans showed lower than required flow rates in the MHCLG (2019b) sample. These dwellings had been occupied for approximately one year, and it is not clear whether the fan flow rates had degraded in this time or had never reached the levels required by ADF. Additionally, 40% of the bathroom or WC extract fans had been switched off at the isolator switch in the system 1 dwellings; the survey revealed that many participants believed that the isolator switch was for everyday use and switched the fan off to prevent it running after they left the bathroom, rather than leaving it on continuously as designed.

A week long PFT measurement was taken in seven system 1 homes, again participants were required to keep trickle vents open and use fans during cooking and bathing, participants were also required to record periods of extended window opening. All but two of these dwellings recorded a lower ventilation rate than recommended by ADF as whole house ventilation rate (MHCLG, 2019b), the two homes recording an adequate ventilation rate reported frequent window opening.

Revisions to ADF have been proposed and a consultation has been released (MHCLG, 2019a). At this point, the new edition of ADF has not been released.

2.3.2 System 3 - continuous MEV

Ventilation system 3 relies on continuous MEV for background ventilation, increased mechanical extract flow rates for extract ventilation and windows for purge ventilation (although increased flow rates may be used in rooms without windows). Air inlets for the continuous extract ventilation are provided through the building fabric and controlled background ventilators, often trickle vents. This system was first included in ADF in 2006, the provisions are the same in the 2010 edition, except that trickle vents are required in the 2010 edition but only recommended in 2006.

DCLG (2010) justified the decision to focus only on system 1 dwellings on the basis that there was particular concern over the use of natural ventilation through trickle vents for provision of sufficient ventilation in increasingly airtight homes. However, MHCLG (2019b) did investigate system 3 dwellings. Similar to the system 1 dwellings fan flow rates were frequently lower than stipulated in ADF, trickle vents were often closed and ventilation was lower than recommended in two of the three homes in which ventilation was measured. Additionally, over 50% of the ventilation systems were not switched on in the system 3 dwellings, reasons included noise nuisance and a belief that the fans were supposed to be switched on as required rather than running continuously as per the design intention.

2.3.3 Recurring problems in ADF compliant homes and critique of research method

Several common themes can be seen in the research conducted by Crump et al. (2005), DCLG (2010), and MHCLG (2019b) to support new editions of ADF. Firstly, this research has not aimed to investigate ventilation in homes as-occupied, but instead focuses on conditions which would apply if the design intentions are followed. Secondly, there is a recurring issue related to participant use of the ventilation system and the discrepancy between this and the design intentions in ADF, both in terms of closing trickle vents and switching off MEV. This is a concern given that the ventilation rates measured in these studies were often inadequate even when the trickle vents and MEV were on (per the first point). Under normal as-occupied conditions many of these homes may have even lower ventilation rates due to closed trickle vents and switched off MEV. This brings forward the need for consideration of dwellings as a sociotechnical entity which will be discussed further in Section

2.5. Finally, the passive tracer gas method was used by Crump et al. (2005), DCLG (2010), and MHCLG (2019b). As discussed in Section 2.2.3.3.1 this method is useful as an indication of the average ventilation in the space, but without measuring the variability of ventilation it is not possible to understand how frequently householders are experiencing inadequate ventilation rates or the extent to which window opening may be mitigating an inadequate ventilation system.

The above review related only to research conducted by the UK Government in support of revisions to ADF, the following section will review a wider base of literature aiming to understand ventilation rates in occupied dwellings.

2.4 Ventilation rate research in occupied homes

The previous section presented the ventilation strategy in ADF and the research that has been conducted to support new editions of the document. The ventilation rate research was carried out in occupied homes, in which the ventilation is expected to vary due to weather and occupant use of windows and fans. Despite this, the ventilation measurement methods used were unable to disaggregate this variation in ventilation rate. This section will consider a wider base of ventilation rate research taking place in occupied dwellings. The limits of this review are drawn around examples from the literature in which the variability of ventilation over time or the influence of occupant actions on ventilation rate are considered. For the same reasons as above, this review considers empirical rather than modelling studies.

This section is split into three parts: the first part will review research which has taken multiple measurements of ventilation in occupied homes and has considered occupants to a limited extent, the second part will review research which has taken a small number of ventilation measurements but placed a greater emphasis on occupants and the final part discusses research in which occupant interactions with ventilation equipment were investigated but there were no measurements of ventilation rate.

2.4.1 Variation in ventilation in occupied homes

As discussed in Section 2.2.3.3.1, Bekö et al. (2016) applied several tracer gas methods in five occupied dwellings, and found significant variability in the ventilation rate over daily periods. Bekö et al. argue that this variability in the ventilation rate is significant because some pollution sources are likely to be variable on similar time scales, meaning that the variability of the ventilation rate and the timing of the pollutant source could have an important impact on the IAQ experienced by occupants. It is uncommon that studies report on such variability of ventilation rates, but this section presents some notable examples.

Dick and Thomas (1951) conducted over 200 measurements of ventilation in 23, naturally ventilated, occupied homes in two streets in England in an early study in which multiple measurements of ventilation were taken in occupied homes. The experimental design was described in Dick (1950); tracer gas decay measurements were carried out using helium, with the measurements being designed so as to minimise the disruption to the life of the occupants. Helium is much less dense than air, so the flow patterns of helium will be different to the bulk air movement, the extent to which this would have affected the results is unknown. Measurements were taken in each of the buildings at random times throughout the heating season and the time period of the decay analysis is unclear. Weather conditions were measured on both streets. Window opening of homes in both streets was observed at random times by the researchers during the day, this was supplemented by occupant records at night in one of the streets. Dick and Thomas (1951) found that the relationships between ventilation rate, weather conditions and number of open windows differed between the two streets studied. Eight detached dwellings were measured on one street in a sheltered location. At this site changes in ventilation rate were dominated by wind effects, with reduced window opening counteracting the effect of increased temperature differences during colder weather; 15 semi-detached dwellings were measured on other street in a more exposed location, and here window opening was less influenced by external temperature and the variation in ventilation rates were related to changes in temperature and wind conditions. Dick (1950) and Dick and

Thomas (1951) note that the specific effect of occupant actions depends not only on the number of windows open but also the orientation of the wind direction relative to window location and the combination of open windows, as well as the opening and closing of internal doors affecting internal air flows.

More recently, Wallace et al. (2002) carried out ventilation measurements using SF_6 decay every two to four hours in an occupied house over a year. A measurement period this long is extremely unusual. This research took place in the home of one of the authors; the method used required pumped gas sampling (which is bulky and noisy) so recruitment of non-researcher participants may have been challenging for a campaign of this length. The dwelling was located in Virginia, USA and was a three-storey, end-of-terrace building, where the lower floor was a partial basement which opened out onto a patio at the back of the house. The external temperature ranged from -13°C to 40°C, a greater temperature variation than for the UK context. The ventilation system is not completely clear, but the paper describes the HVAC (heating, ventilation and air conditioning) system as using 100% recirculated air which is ducted around the house. Warm air heating systems are much more common in the USA than in the UK. The dwelling also had an attic fan which operated above 27°C to remove warm air. No other HVAC equipment is described so the dwelling is thought to be naturally ventilated most of the time. The mean ventilation rate was 0.65 ach, with a standard deviation of 0.56 ach ($N \sim 4600$) showing the considerable variability in ventilation over extended periods. Wallace et al. (2002) found little effect on the ventilation rate from the wind speed and direction and a small effect from the internal-external temperature difference. Wallace et al. (2002) acknowledge that poor records of window and door opening was a major limitation of their study.

Howard-Reed et al. (2002) measured the effect of window opening in two occupied homes. One was a detached two-story dwelling in California, USA and the other was the same dwelling that was used in Wallace et al. (2002). In both dwellings, the HVAC system was switched off during the measurement periods, so the experimental conditions reflected natural ventilation. The window use was controlled by the authors so occupant window use was not explored in this study. Similar to Wallace et al. (2002) the authors found the wind had a minimal effect on the ventilation rate. However, Howard-Reed et al. (2002) used weather data from weather stations at nearby airfields, and noted that the influence of the external weather conditions will depend significantly on the very localised topography and obstructions around the building of interest, so that an extension of this result to other dwellings is not necessarily valid. Wallace et al. (2002) explored this further and compared wind measurements taken 1m above the roof with data from a nearby airfield, they found Spearman correlation coefficient for wind direction was 0.68 and for wind speed was 0.30.

Almeida et al. (2020) took 132 ventilation measurements in two rooms of an occupied house using SF_6 tracer gas decay when the building was unoccupied. Measurements were conducted in two configurations, one with the doors to the measurement rooms closed, and the other with all doors in the building open. Windows were closed during all measurements. Although the measurement description is slightly unclear, it seems that the measurements were conducted with the tracer gas released and well-mixed only in the measured room, so that the resulting ventilation rate results are a combination of indoor-outdoor airflow and airflow through the open door into the rest of the building, and the effect of internal airflows is likely to dominate for the doors open results. Almeida et al. (2020) found that the doors closed ventilation rates varied between 0.02 ach and 0.21 ach, while the doors open rates varied between 0.23 ach and 1.40 ach. In both cases, the variation in ventilation rate was correlated with the wind speed, temperature differences were similar during all measurements and did not have a large effect on the results. This work highlights the considerable influence of internal door closure (which is determined by occupants) on ventilation rate, however door use is not something that has been widely taken into account in studies of ventilation in homes (Howieson et al., 2014). Almeida et al. (2020) conclude by cautioning against one-off measurements of ventilation as these may be misleading.

The above studies have all conducted a large number of ventilation measurements and considered the variability of ventilation due to weather conditions and directly or indirectly have considered the influence of occupants on the ventilation rate. However, the depth of attention to the occupants has been limited with only Dick and Thomas (1951) directly observing the window use of occupants. The other studies have considered the effect of use of doors or windows but did not explore occupant use of these openings. The following section discusses further studies of ventilation in homes which have focused less on the variability of ventilation but more on the occupants.

2.4.2 Ventilation studies with few ventilation measurements

Iwashita and Akasaka (1997) carried out measurements of ventilation rate using a constant concentration of SF_6 tracer gas in two or three rooms of eight Japanese dwellings over a period of two or three days during the summer cooling period. External conditions were considered to the extent that they influence window opening and the influence this has on ventilation. A questionnaire was used to gather data on timings of window and door opening, air conditioning use and the thermal comfort of the occupants over the measurement period. However, no evidence is given that questionnaires were developed in line with best practice for this method, which may affect the results. Nonetheless, Iwashita and Akasaka (1997) found that ventilation rates were similar when these dwellings were unoccupied, but that large variations in ventilation rates were observed during occupied hours. This was due to significant differences in window use, door use and air conditioning use between the participants. This study highlights the various ways people respond to conditions in their homes and how this affects the ventilation in the space.

Bekö et al. (2010) measured metabolic CO_2 concentration in 500 children's bedrooms in Denmark for an average of 2.5 days to investigate the association between overnight ventilation rates and asthma. Participants were asked to keep a diary recording the number of people in the measured room during the day and night, whether anyone left the room for a long period in the night, positioning of the doors and windows during the measured days and nights and the weights and heights of all occupants who slept in the measured room. As above, this study does not make reference to developing this diary in line with best practice, which may affect the results. Ventilation rates were measured using the build-up, equilibrium and (occasionally) decay tracer gas techniques. Bekö et al. did not identify any relationship between the outdoor temperature and the ventilation rate, but found that ventilation rates tended to be higher when more people were reported to be sleeping in the measured room. This was associated with a reported increase in window opening. Bekö et al. emphasise the bias in the measurement due to the possibility of internal airflows and air exchange with other spaces in the building which may not have outdoor concentrations of CO_2, particularly as the majority of the bedrooms studied had doors open overnight.

Sharpe et al. (2015) investigated ventilation and the actions of occupants in detail. This was a tiered study in which 40 newly-built naturally ventilated Scottish dwellings were monitored over two days. These were a subset of 200 naturally ventilated homes in which structured interviews were conducted by a social survey company. The Scottish Domestic Handbook (BSD, 2017) requires mechanical extract ventilation and trickle ventilation in naturally ventilated dwellings, this is similar to ADF but the exact provisions are quite different. In particular the equivalent area of trickle ventilation is at least twice the minimum area required by ADF. Ventilation rates were estimated using the overnight equilibrium CO_2 concentrations. The method was discussed in more detail in Section 2.2.3.3.3 where it was suggested that there are considerable issues with the accuracy of the method. Nonetheless, Sharpe et al. (2015) estimated that 42% of the dwellings in their sample had overnight ventilation rates less than 0.5 ach on the days measured. Additionally, CO_2 concentrations over 1000 ppm were recorded in all of the 40 monitored bedrooms including where windows were open. As discussed in Section 2.2.2 CO_2 concentration over 1000 ppm is sometimes interpreted as indicative of inadequate ventilation rate. Rooms with windows closed with trickle vents open showed slightly lower CO_2 concentrations compared to windows and trickle vents closed.

The interview results showed that many of the participants took actions overnight, such as closing windows or blinds, which would reduce the airflow from windows or trickle vents if they were open. Bedroom doors were also often closed, limiting the possibility for cross-ventilation or volume dilution of pollutants. The study found that 92% of participants considered the indoor air quality in their bedrooms to be good or very good, despite the high CO_2 concentrations measured in the sub-sample of monitored homes discussed earlier.

Sharpe et al. (2015) found that occupants were primarily using windows for ventilation rather than trickle vents. There were several reasons given for using windows, with the most common being that the room was too warm. Other reasons included removing moisture or smells, for drying clothes or for fresh air. Reasons for not opening the windows included reducing heat loss, noise, security and pollution. In terms of the trickle vents, Sharpe et al. (2015) found 63% of participants left trickle vents closed all the time, the most common (41%) reason given for keeping them closed was 'don't feel the need to open the vents', followed by a lack of awareness or knowledge (32%). Other reasons included avoiding noise from outside, worries that the heating bill would increase, that they would make the house too cold or an inability to reach them. Inaccessibility was identified as a problem particularly for the elderly participants. About 25% of participants left trickle vents open all the time, and about 10% reported interacting with them on a weekly basis. The study found that 82% of the participants could not recall being given advice on ventilating their home, and of those that could only 40% recalled being told to keep trickle vents open. All of the trickle ventilators in the bedroom were occluded at night by some form of curtain or blind, and over half of the dwellings studied had bedroom doors closed overnight, reducing the possibility for cross ventilation or volume dilution of pollutants.

Foster et al. (2016) monitored Passive Houses with MVHR in Scotland finding several issues with the ventilation due to installation and occupant use. Four of the five systems they studied were improperly balanced (meaning air supply flow rates did not match air extract flow rates) and there was a lack of occupant understanding leading to improper use. They suggest occupants must be better informed about the MVHR system in terms of operation and interaction as this would help occupants to identify when there is a problem, and that better systems for checking installation, commissioning and handover are required.

All the literature referred to in this section are primarily technical studies, there has been limited insight into why the participants do what they do, and little to no exploration of how the actions which influence ventilation are bound up in the occupants' lives.

2.4.3 Studying occupant interactions with ventilation technologies

There have been several studies on the interactions building occupants have with various ventilation technologies. Fabi et al. (2012) reviewed the literature on drivers of occupant use of windows. They found that most research has focused on the effect of environmental conditions on window opening in office environments and they argue that further research in homes would be beneficial given the amount of time people spend in this environment. Additionally, Fabi et al. (2012) found that a wide variety of environmental conditions - including temperature, lighting, olfactory and auditory - can all contribute to occupant use of windows. These wider factors make up the indoor environmental quality (IEQ) which is an important component in human comfort, various authors have attempted to rank the relative importance of these different factors (Frontczak and Wargocki, 2011; Mujan et al., 2019). These issues are interrelated but it may be challenging to combine insights relating to different parameters, for example Mavrogianni et al. (2015, p. 317) find that 'such issues are, nevertheless, usually examined in isolation and synergistic effects between summertime ventilation behaviour, indoor temperature and air pollutant concentration have been under-investigated to date'. These various environmental conditions are likely to be significant factors in the ways that occupants ventilate their homes using various ventilation technologies.

Internal doors have been studied infrequently, although they may have a significant impact on ventilation experienced by occupants because they affect internal pressure differences. Banfill et al. (2012) took a user-centred design approach to studying user requirements in dwellings retrofitted with MVHR systems, they carried out two in-depth interviews with adult household members in 20 dwellings which were purposively sampled to give a variety of house types, household types, age ranges, incomes and locations. They found that many participants closed specific doors at night time, while other doors were routinely opened or closed at particular times. For instance, after children grew up and left home the doors to their rooms were often closed for months at a time. Banfill et al. suggested that the closure of internal doors could lead to poor circulation of air and reduced efficacy of the ventilation system, although habitual closing of internal doors would likely affect the ventilation regardless of the system in place. McDermott et al. (2010) used semi-structured interviews and questionnaires to investigate how occupants interacted with self-closing fire doors. Many of the participants understood why closing fire doors were important for fire-safety but almost all the participants tampered with the self-closing mechanism and regularly left doors open. They found a variety of reasons that occupants tampered with the self-closing mechanisms including inconvenience, noise associated with slamming, inadequate light transmission, prevention of finger trapping in closing doors and strength required to open the doors. Some participants stated that they were particularly concerned about the closing doors when young children were present; either because the adults needed to be able to see the children at all times or because of finger trapping concerns.This study highlights the problems that can arise when a technical solution is used without adequate consideration of how people actually live in their homes.

Discrepancies between design intentions and as-occupied use of equipment was also studied by Baborska-Narozny and Stevenson (2017), who investigated continuous mechanical ventilation (MV) systems, MVHR and continuous MEV. They combined several methods, including on-site surveys, monitoring of a subset of dwellings for several months and occupant interviews. They interpreted these data using Social Practice Theory (Schatzki, 2010) and Bruno Latour's concept of human and non-human actors (Latour, 2005) to identify key elements influencing whether continuous MV systems were used as designed; these included experiences with ventilation systems in previous dwellings and strategies for learning about new ones, feedback from ventilation systems regarding energy use and perceptions of the MV systems as necessary or a nuisance.

Fox (2008) conducted structured interviews with the occupants of 40 dwellings with trickle vents and intermittent mechanical extract fans in Cambridge. She found that the occupants were closing the trickle vents during the winter to avoid cold draughts and not reopening them in the spring. Behar (2016) found several issues related to the way trickle vents had been integrated into everyday life; some occupants closed trickle vents despite recalling being told to keep them open (deliberately taking actions at odds with the design intention), some only opened them in winter, others only in summer and others all year round. Additionally, furniture had sometimes been placed in front of trickle vents, which obstructed the airflow, sometimes this was an intentional attempt to reduce heat loss through drafts. Other participants in Behar's study were pleased with the trickle vents as they offered the ability to ventilate a space while leaving the windows closed, thereby maintaining security.

The above insights from Behar (2016) were part of a wider study which used a social practice theory (SPT) approach studying whole dwelling ventilation systems in homes, she argues that the wide variety of influential factors embedded within everyday life can be interpreted within this framework. Behar conducted in-depth qualitative interviews with occupants of a series of dwellings with different ventilation strategies. These occupants had all been given advice on the running of their homes. She found that ventilation was influenced by a range of factors, from window closing to stop insects coming in, concerns about safety, removal of cooking smells to window opening for a sense of connection to the outdoors. Behar identifies a challenge in investigating ventilation in isolation as the activities related to it are highly interconnected with other parts of the socio-technical arrangement.

The present section has discussed research which has considered ventilation rates in occupied homes, either by measuring them or by considering the effect of occupant actions on them (or a mix of both). The following section will consider research which combines social and technical research in the built environment in more detail.

2.5 Sociotechnical research, social practice theory and ventilation

People can have considerable impact on ventilation in homes. However, the research reviewed in the previous section generally included limited integration of physical results with insights about the actions of the occupants, and there was a lack of research which combined detailed ventilation measurements with detailed investigation of occupant actions. Moreover, Section 2.3.3 showed that the research supporting changes to ADF often identified discrepancies between the ways occupants ventilated their homes and ADF intentions, but these were not studied in detail. These studies primarily used a physical perspective to investigate ventilation. The philosopher Mary Midgley argues that physical science gives us ‘a view seen through a single window, a set of photos taken from a particular viewpoint. In order to use it we always need to put it together with a background from the other sciences’ (Midgley, 2018, p. 94). In a similar vein, Behar (2016) showed that novel insights about ventilation in homes may be drawn by a deeper integration of social and technical research, she used a social practice theory lens to do this. This section reviews why it is useful to combine social and technical perspectives in research studying physical parameters in domestic settings, and why social practice theory is useful in this context.

Sovacool et al. (2015) assert that social research has generally been undervalued in energy research (broadly defined). They suggest that research to support a transition to a sustainable, just future which enhances well-being will require integration of insights from physical and social sciences. Sovacool et al. argue for a greater diversity of perspectives to give depth to our understanding of energy related problems. Pellegrino and Musy (2017) similarly states that, naïvely considered, technological developments should have led to significant reductions in energy consumption in recent decades but such reductions have not been observed. They argue that the social factors affecting rising consumption have traditionally been ignored.

While energy research has been overwhelmingly dominated by physical and technical research, there are growing calls for a greater emphasis on social research both in its own right and combined with technical research (Sovacool et al., 2015). Love and Cooper (2015) find that the term ‘socio-technical’ has generally been used in referring to the interaction between social and technical components and argue that physical and social factors are inexorably linked in energy use in buildings, whereas Lowe et al. (2018) argue that social and technical systems each form the context for the other and constitute a socio-technical regime. Both argue that research which explores both technical and social aspects will be necessary to untangle the complex system of energy use in buildings. Although these papers focus on energy use, the points they raise are relevant to the present work on ventilation; firstly because ventilation has a role to play in the energy use of buildings, and secondly because ventilation research has also been overwhelmingly dominated by a physical approach even though occupants have a significant role to play.

Many social science disciplines have been used to investigate various aspects of domestic energy use. For example traditional economics, behavioural economics, technology diffusion, social psychology and sociology have all been used in models of decisions regarding residential energy use (Wilson and Dowlatabadi, 2007). However, relatively few social theories place significant emphasis on the *material* as well as social domain. Science and technology studies (STS) explores the role of science and technology in society (Sismondo, 2009), but does not investigate the detail of everyday actions. Social practice theory (SPT) has been widely used in exploring different aspects of energy use in homes, from heating (Gram-Hanssen, 2010a; Kuijer and Watson, 2017) and cooling (Strengers and Maller, 2011), the emergence of daily showering (Shove and Walker, 2010) and energy efficient refurbishments of homes (Bartiaux et al., 2014). These authors have taken care to analyse how the technical landscape has influenced the social structuring of human life, albeit with differing degrees of emphasis. SPT provides a route for studying the actions of occupants while maintaining an emphasis on the physical arrangements. Section 3.4 argues Social Practice Theory is an appropriate framework for this research and the remainder of this section focuses on this theory.

Shove and Walker (2010) argue that social and technical arrangements strongly influence each other, using social practice theory (SPT) as a framework. They offer the evolution of washing as an example to illustrate their point; it is now common to shower everyday while a generation ago a weekly bath was the norm. Shove and Walker argue that there have been changes in technical aspects: hot water and electricity supply; power showers; tiles; screens; dedicated spaces for showering, but that these changes alone cannot explain the change in people's routines. They identify an evolution in the meanings of showering, associated with propriety, morality, freshness and relaxation as well as changes in the ordering of the day: routines associated with getting up, getting ready to go out or exercise. Shove and Walker argue that these aspects must be studied together in order to grasp the forces at work in this changing practice, labelling this a socio-technical transition.

Lowe et al. (2018) also use SPT as the framework for analysing social data and the lived experience of participants in their retrofit study, but argue that this lived experience does not make sense without understanding the 'technical systems that *co-constitute* them' (Lowe et al., 2018, p. 472). An outline of social practice theory is presented in the following section, and Section 2.5.2 discusses SPT research specifically related to ventilation.

2.5.1 Social practice theory

Social practice theory has been described as a 'fragmented body of theories' (Gram-Hanssen, 2010a, p. 176) which analyse actions and expressions rather than signs and symbols. The authors above (Shove, Gram-Hanssen, etc.) draw extensively on the various works of Schatzki (Schatzki, 1996; Schatzki, 2002; Schatzki, 2010) in which he outlines his version of social practice theory. Schatzki (2002) describes a practice as an organised nexus of doings and sayings, examples of which include cooking, banking and commuting. A practice can be thought of as collection of things which people do, talk about, know about and which have intended outcomes and are part of a common social understanding of what it is to do that practice.

In this way, the actions or thoughts of individuals are no longer the central unit of analysis, rather an understanding of how society views these practices is sought.

In Schatzki's conception, practices are a set of doings and sayings comprised of three elements: **practical understandings**, **rules** and **teleoaffective structures**. Schatzki focuses on people's actions - doings and sayings - as a way to understand how social life is organised. Doings are the actual bodily actions that people perform with their hands, arms, legs and any prosthetics they may use (e.g. walking, using switches, moving things); sayings are doings that communicate something (e.g. speaking, nodding, winking). A basic doing, such as the wave of a hand could amount to greeting or asking someone to come over depending on the context, in which case greeting or asking would be actions. Schatzki sees practices as organised nexuses of doings and sayings made up of the three elements above.

Practical understandings relate to the abilities one needs to have in order to carry out a particular practice. These abilities include 'knowing how to X, knowing how to identify X-ings, and knowing how to prompt as well as respond to X-ings' (Schatzki, 2002, p. 77), where X is a doing, saying or task involved in carrying out the practice. Examples of practical understandings include printing, mixing, labelling and storing.

Rules according to Schatzki (2002, p.79) are 'explicit formulations, principles, precepts, and instructions that enjoin, direct, or remonstrate people to perform specific actions'. Examples of rules include: respect for elders, keep the workplace tidy, or that certain members of an organisation do not have to disclose information to everyone in the organisation.

Finally, teleoaffective is a compound of teleo: having a purpose or goal; and affective: having a meaning. A particular practice 'always exhibits a set of ends that participants should or may pursue, a range of projects that they should or may carry out for the sake of these ends, and a selection of tasks that they should or may perform for the sake of those projects' (Schatzki, 2002, p. 80). Ends could include things like making a profit or keeping equipment functional. These ends are the goals that people are trying to achieve and achieving these is meaningful to the people.

For Schatzki then, practices are a collection of doings and sayings which are organised by the above three elements. Practices are teleoaffectively structured in that participants pursue particular ends, and carry out certain projects for the sake of these ends. These projects may be further broken down into tasks, the carrying out of which depends on the practical understandings of the participants and are performed within the rules the people are subject to. Within a practice there are a range of possible ends, projects and tasks that participants may be involved with, and these may be carried out using a range of doings and sayings so it is not necessary that two participants of a practice follow the same course of action. For two participants to be carrying out the same practice it is only necessary that their actions be structured by the same nexus of **practical understandings**, **rules** and **teleoaffective structures**.

Schatzki's approach is philosophical and various authors have renamed, broken down or added new elements when utilising practice theory in empirical research. The authors above who have used SPT in the context of energy use (Gram-Hansen, Shove, Kuijer, etc) have particularly emphasised the role of the **material** in shaping energy consuming practices, and have usually explicitly added the material as another element in practices. For example, Shove and Walker (2010) emphasises the role of technical developments in household plumbing, hot water supply, shower screens and personal hygiene products in shaping how society has moved from a once-weekly bath to daily showering.

An example from Gram-Hanssen (2010a) shows how the elements can fit together to give insights into domestic life: Gram-Hanssen combined technical data relating to the energy consumption and indoor temperatures of five very similar dwellings with qualitative interviews about home heating to explore differences between the cases. Gram-Hanssen extends the rules element to include formal knowledge. One family with a high energy consumption and high indoor temperature wanted the home to be warm and cosy (meaning), they have a good understanding of how the system works and control the heating system (technology) in a very systematic manner (practical understanding), they are well aware how much energy they use from reading their meters and their bills (rules and knowledge) but have little regard for the amount of energy they use (meaning) so do not adjust their heating practices to reduce their consumption. This contrasts with another family who have very low energy consumption: this family is concerned with saving money (meaning) and like to keep particular rooms warm (meaning) so close doors (technology) to keep heat in these spaces (practical understandings). This family also adjust the heating to come on in specific parts of the home at specific times depending on where they need heat (practical understandings). They are familiar with the technical aspects of the heating system (technology) having acquired this information from a folder distributed to all houses some years before (formal knowledge). Although the physical buildings and technology installed in both dwellings is very similar, the SPT framework helps to draw out the different ways of living that each family has and how this combines to give very different energy uses.

Social practice theory allows reflection on the shared meanings and developments through which patterns of everyday doings emerge and are sustained. While the approaches of the authors referred to in the first two parts of Section 2.4 can be useful in giving a sketch of what is happening in homes, SPT offers a much more detailed and sensitive picture of how and why technology is used in different homes.

This section has discussed social practice theory in general, referring to the work of Schatzki upon which later authors have often leaned. The following section will focus more specifically on the literature in which ventilation has been analysed with a social practice theory lens.

2.5.2 Ventilation and social practice theory

Previous authors have studied domestic practices which are likely to influence ventilation rates.

Hauge (2013) studied people's use of fresh air and airing practices in their homes in Denmark, with a phenomenological focus on how fresh air is experienced. She discusses the routinised aspects of airing practices, how opening windows is often associated with other tasks or daily activities like waking up, showering, making the bed or cleaning, though these routines may change with the seasons or with the weather (for example the airing associated with clothes drying varies depending whether it is raining). The specific demands of different houses were also seen to play a role in shaping the development of airing practices through a lifetime, for example the formation of condensation on single glazed windows drove frequent airing in an old home but this was replaced by much less regular airing in a newer home with a mechanical ventilation system. Hauge found that the sounds coming in through the window helped to orient the participants spatially by hearing the sounds of the city going by or hearing nature in rural locations. The sounds also oriented the participants in time; with birdsong varying through the day and the year. Hauge found there were also clear social implications of creating the impression of freshness and healthiness in the home through airing as opposed to the risk of an impression of stagnant, damp, humid and decaying smells in home. Letting in fresh air is seen as a way to revitalise the senses, to freshen, and almost as a part of cleaning the home. Safety concerns can also drive airing practices, for example the need to remove radon requiring that windows are open, whereas concerns about outdoor air quality, smog or fumes from industrial processes, requiring that windows are closed. Through her article, Hague shows how air and airing practices are associated with utility and tasks in the home, with sensory satisfaction and with social meaning. Hauge finds that ‘we listen to our environment through air, by using our bodies and senses and by paying social attention to it’ (Hauge, 2013, p. 184).

Hauge (2013) focused on fresh air with a discussion of the invisibility of air and coming to know it through senses, Royston (2014) similarly discusses coming to know heat and heat flows through interaction with the senses. Royston focuses on the practical understandings or know-how element of practices involving managing heat-flows in the home, these practical understandings include those related to sensing heat and heat flows (through thermal sensations but less obviously through seeing ‘dragon’s breath’ when speaking, candles flickering indicating draughts, speed of snow-melt on roofs or the smell of a cold and damp room). These were related to managing heat and heat flows to stay warm at home, knowing how and when to use radiators, valves, doors, windows, curtains, clothes and improvised solutions including draught excluders made from old clothes, fans to blow air across a radiator or bed-warmers made from hot water in wine bottles. Royston discusses three ways these practical understandings change over time. Firstly changes over the course of a lifetime; older people may require warmer temperatures and the arrival of children influences ways of keeping warm. Secondly changes in material arrangement, particularly moving house, can require new ways of knowing how to manage the indoor environment. An older house may be draughty and cold requiring certain ways of maintaining appropriate temperature very different to those that must be learned if moving to a new, highly insulated and airtight home which may require ways of keeping cool and encouraging more airflow; in this way a new or updated set of practical understandings must be developed for living in a new home. Finally, changing norms and conventions are seen to affect practical understandings over time, for example a common perception among older people is that sleeping with the window open is healthy. Although the focus here is on heat flows from an SPT perspective, much of this discussion is relevant to considering ventilation in an SPT framework. This is not only because heating and ventilation are so closely linked through the interaction of indoor and outdoor air and temperature but also because of the invisibility of temperature and air. This means other senses and routes must be used to facilitate management of heat flows and air flows, Royston's paper shows how the practical understandings element of SPT can capture this.

As discussed in the previous section, Gram-Hanssen (2010a) studied home heating practices and this revealed ways that heating practices interact with ventilation. Her analysis is strongly structured around the four elements of practices discussed in the previous section. Meanings associated with ventilation were found to relate to healthiness, freshness and proximity to nature in keeping with the findings of Hauge (2013). Gram-Hanssen (2010a) found practical understandings involved both regular airing associated with particular activities (smoking, coming home, cooking, etc), and more sensory practical understandings in which windows were opened in response to cues such as smells of dampness. Rules and formal knowledge were less discussed by Hauge (2013) and Royston (2014) but Gram-Hanssen finds that airing practices have been influenced by information from non-governmental organisations about airing for asthmatic people, by media campaigns and by instruction from parents. The technical aspect of ventilation is little discussed in Gram-Hanssen (2010a), with the focus placed on the heating system instead.

In contrast, Behar (2016) took a sociotechnical approach to whole house ventilation practices in energy efficient homes with a strong focus on the technical and physical arrangements. She found a disconnect between the way ventilation systems had been designed and how they had been incorporated into the lives of the participants. MVHR ducting had been squashed by possessions stored in the same place, wall mounted trickle vents had been obscured by arrangements of furniture and door undercuts had been blocked up. Without focusing on the intended technical design these details could easily have been missed.

Some common themes have emerged from the above discussion of ventilation within a practice theory framework. Firstly, the importance of fresh air for ridding unwanted and socially unacceptable smells has emerged, where airing is associated with feelings of freshness, cleanliness and health. Secondly, airing is involved in common tasks or as part of the ordering of the day. Thirdly, air and airing are interpreted in several dimensions, including smells, freshness, humidity, temperature and sounds. Moreover, the qualities of the outdoor air are important to how the occupants air their homes: letting fresh air in through open windows sometimes provides a pleasant connection to the outside world, through which the sounds and smells of nature can be enjoyed; in other cases the air outside is deliberately shut out for example when the outdoor environment is perceived to be polluted, or to create a warm and cosy home environment in the winter. Finally, the ways in which people interact with and interpret air throughout their lives has been shown to vary given the material arrangement and specific demands of their present and previous homes. Through these papers the richness of everyday experience at home in relation to air and ventilation begins to emerge.

None of these studies of practices relating to ventilation have investigated the physical performance of ventilation systems. Behar (2016) placed most emphasis on the material dimension but she did not carry out any physical measurements of the ventilation systems. Nor did she directly compare the participants' practices with the intentions set out in ADF, focusing instead on the intention of the design team involved in the case study dwellings she investigated. Although ADF is primarily a technical document, it provides details of ventilation systems to be installed in occupied homes, and in doing so ADF makes a number of assumptions about the actions occupants will take. There is a gap in understanding how the domestic practices relating to ventilation compare to the assumptions ADF makes regarding ventilation in occupied homes. This is problematic given that in Section 2.3.3 it was shown that participants often did not take the actions that ADF expects and that this may affect the ventilation rates occupants experience.

The following section will summarise the discussion in this literature review, detail the identified gaps in the literature and the research questions posed in this thesis.

2.6 Summary and research questions

Through this chapter, the physical basis of ventilation and ventilation measurement has been explored. Ventilation comes about as a result of pressure differences between inside and outside driving air movement either through unplanned air leakage paths or through planned ventilation technologies. These pressure differences are driven by wind, temperature differences and mechanical fans. These pressure differences will be variable through a day resulting in changes to the ventilation rate, unless mechanical ventilation strongly dominates the driving forces. Ventilation measurement methods were then reviewed, and it was shown that estimating ventilation from air permeability measurements, threshold CO_2 concentrations and passive tracer gas methods do not give insights into this variation. This can be problematic because the extent to which the result is skewed by extremes is unknown, the result cannot be disaggregated between the different types of ventilation set out in ADF (purge, extract and whole dwellings), nor can the ventilation rates experienced by the occupants when they are present be resolved. Other tracer gas methods, including the concentration decay and constant concentration methods, have been used to give more insight in this space.

Next, two common ventilation strategies, intermittent MEV (system 1) and continuous MEV (system 3), included in Approved Document F (ADF) to the Building Regulations were discussed along with the historical developments of these strategies. The research supporting new editions of ADF was critiqued. The research showed that occupant operation of the ventilation systems was known to contrast with the designed intention at least since 1995. In addition, the research supporting new editions of ADF consistently made use of the PFT tracer gas methods in which the variability of the ventilation could not be explored.

Further technical ventilation rate research was then discussed, finding a limited volume of literature in which time-resolved measurements of ventilation rate have been collected in occupied homes over an extended period. In the few examples where this has taken place, there has been little investigation of the occupants' interaction with the home in ways which might affect the ventilation rate (doors, windows, fans and vents). Other research in which ventilation was measured over short periods has sometimes sought to investigate these issues.

It was noted that much of the technical research discussed above took a simplistic approach to integrating technical and social perspectives, often with little emphasis on social research methods or theories. There have been calls for more integration of social and technical research to give insight into the co-dependencies of social and technical systems in everyday life (Sovacool et al., 2015; Pellegrino and Musy, 2017; Lowe et al., 2018). Section 2.5 demonstrated that Social Practice Theory (SPT) can be a useful lens through which to carry out such research as it can place significant emphasis on the material dimension at the same time as allowing the study of everyday, routine and commonplace actions.

SPT emphasises analysing people's actions and expressions; practices (organised collections of doings and sayings) are the central unit of analysis. The focus is placed on actual bodily doings and sayings, and there is space for exploring the role of physical arrangements in shaping practices. Schatzki's conception of practices as organised nexuses of doings and sayings made up of teleoaffective structures, rules and practical understandings was briefly sketched, drawn from Schatzki (1996; 2002; 2010). We then reviewed the modifications and extensions to SPT made by various authors working on practices related to everyday energy consumption, particularly highlighting how the material dimension (products, things and technologies) has been added as an explicit element of practices.

Finally the SPT literature relating to ventilation practices was discussed. These accounts offered insights into the ways ventilation is incorporated into everyday life and how it is imbued with meaning in the lives of the participants. However, only Behar (2016) gave a strong account of the material dimension of the ventilation practice with a focus on the specific technologies, layout of the homes and intended strategy for ventilation when the homes were built. While Behar offers this detail in the technical and material dimension, she does not combine this with measurements to assess the physical performance of the ventilation system. The rich insights available using an SPT framework would be useful in comparing ADF's intentions for ventilation in occupied homes with occupants' practices related to ventilation. This would fit well with the primarily technical research in the rest of this thesis.

Through this review several themes and gaps in the literature have emerged. The overall aim of this thesis is to improve methods for evaluating ventilation in occupied homes, and to apply this to case study dwellings to explore the efficacy of ventilation and related occupant practices. The research therefore aims to develop a fuller picture of ventilation rates and their variability as experienced by occupants. Additionally, this research undertakes to compare participants' practices related to ventilation with assumptions made in regulations designed to ensure adequate ventilation in homes, taking ADF as the example. By carrying out this comparison alongside a detailed physical investigation of ventilation, the interconnectedness of the technical and social contexts emerges, thereby giving a detailed and multi-faceted picture of ventilation in homes as-occupied. This thesis will contribute to these issues by addressing the following three research questions:

1. How can temporally resolved, long-term measurements of ventilation be taken in occupied homes?
2. Is the ventilation rate adequate in case study homes and how does this vary over time?
3. Does the way ADF assumes ventilation will be carried out at home adequately capture actual ventilation practices?

This chapter has set the context in terms of the theory, research and regulatory landscape in which this thesis is situated, and from which these research questions have emerged. The following chapter will present the research design intended to address these research questions, discuss the choice of methods and analytical frameworks and present the methods and case studies.

Chapter 3

Methodology and Methods

The literature review in the preceding chapter presented the landscape in which this research is situated, one in which social and technical phenomena are seen to play a part in affecting ventilation in dwellings. Research questions one (measurement of ventilation in occupied homes) and two (adequacy of ventilation in occupied homes) are technical in nature, while research question three (comparison of occupant actions with ADF assumed actions) is primarily social. These questions are held together by the overall aim of improving methods for evaluating ventilation in occupied homes. This chapter will present the research methods that have been used to answer these questions.

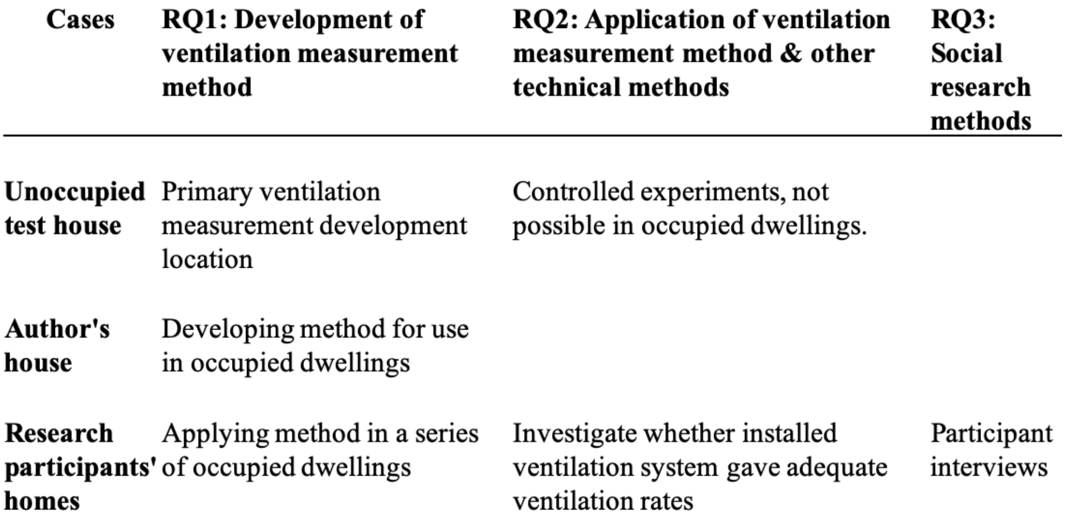
The overall design of the research will first be discussed. It will be argued that a multiple case study research design utilising mixed methods is appropriate since this will allow the detailed approach necessary to explore ventilation from different disciplinary perspectives. The ventilation measurement method will then be discussed in Section 3.2, including the ways that the metabolic CO_2 decay method has been developed for this research such that analysis of long-term temporally disaggregated ventilation rates in occupied homes could take place. The application of the ventilation measurement method and methods used to assess other relevant physical attributes of the case study dwellings to address research question two are presented in Section 3.3. The collection of relevant social data will then be addressed in Section 3.4, with the choice of data collection and analysis method presented and justified. The insights from practice interviews will be briefly presented in discussing how these shaped the final interviews. Research ethics are addressed in Section 3.5. Finally, the details of the case studies and data collected are presented in Section 3.6.

3.1 Multiple case studies and mixed methods

Ventilation in occupied homes comes about as a result of both physical conditions (weather, air permeability, fan power, flow through open windows) and social conditions (operation of fans, windows, doors) as discussed in Section 2.4. The research aim of improving methods to evaluate ventilation in occupied homes therefore will be addressed by considering the physical ventilation rate as well as social factors related to ventilation. This clearly points to the need for mixed methods research. While there are many calls for mixed methods in energy research, there is less discussion of how to integrate findings from different disciplines (Pellegrino and Musy, 2017). This research takes a pragmatic philosophical stance to the interpretation of data from multiple methods; pragmatism ‘orients itself towards solving practical problems in the “real world” ’ (Feilzer, 2010, p. 8). Findings from the physical measurements and social data were combined to investigate the practical problem of assessing the adequacy of ventilation in occupied homes.

Lowe et al. (2018) advocate a pragmatic stance to the interpretation of results from mixed methods, and argue that case study research is an appropriate form for such research. Case study research takes a small number of examples and examines them in detail, but this can carry some disadvantages. Most obviously, studying a small number of cases means that findings may not be generalisable. Flyvbjerg (2006) points out that that this is not always true and gives Karl Popper’s example of critical cases - if I assert that there are only white swans and then see one black swan then I can reject my initial assertion and say that in general there are not only white swans. Besides this, Flyvbjerg also argues that generalisation is only one of the routes by which knowledge is gained and accumulated, and that the depth of description possible in case study research is of value in forcing a rigorous description of phenomena.

Table 3.1: Showing the research questions, the case study dwellings and the main aspects of the research associated with each.



Cases	**RQ1: Development of ventilation measurement method**	**RQ2: Application of ventilation measurement method & other technical methods**	**RQ3: Social research methods**
Unoccupied test house	Primary ventilation measurement development location	Controlled experiments, not possible in occupied dwellings.	
Author's house	Developing method for use in occupied dwellings		
Research participants' homes	Applying method in a series of occupied dwellings	Investigate whether installed ventilation system gave adequate ventilation rates	Participant interviews

Flyvbjerg (2006) also argues that part of the value of case study research is that it can highlight contextual and interrelated issues which could be lost in summarising information or evidence from a large number of cases. Lowe et al. (2018) argue that studying multiple case studies with an interdisciplinary approach can provide rich insight into building performance and that a case study can be an appropriate 'holder' for mixed methods. Gerring (2007) finds that this ability to employ a variety of techniques within case study research 'lends that research its characteristic flexibility' (Gerring, 2007, p. 33). Case study research allows a detailed approach which facilitates a breadth and depth of insights from different methods. The gaps identified in the literature review pointed to limited research which explores ventilation in detail, a lack of methods to facilitate this and a lack of detailed integration of social and technical perspectives. A case study research design is appropriate for undertaking this kind of detailed work.

Different aspects of the research were addressed in different case study dwellings, and the key aspects are presented in Table 3.1. To address the first research question an existing ventilation rate measurement method was developed to facilitate analysis of time-resolved measurements in occupied dwellings over extended periods. This part of the research is technical and some aspects made use of an unoccupied test house because this allowed controlled experiments and known conditions without causing disruption to occupants. The second (adequacy of ventilation rate in occupied homes) and third research questions (comparison of ventilation practice with ADF intention) were investigated in the same set of occupied homes. The second question was addressed using technical methods to characterise the physical aspects of the dwellings and measure the ventilation rate specifically using the method developed in answering the first research question. The impact of a series of potential occupant actions on ventilation rates was also investigated experimentally in an unoccupied test house. The third question was addressed using social research methods to understand the ventilation practices of the occupants of the occupied homes. Finally, the learnings from research questions two and three were drawn together to give a rich and detailed picture of the sociotechnical aspects of ventilation in these occupied homes.

The following sections set out in detail how the different strands of the research were carried out and details of the case study sites are given at the end of the chapter.

3.2 Ventilation rate research: method development

Section 2.2 presented several common methods for ventilation measurement. However, research applying these methods has rarely aimed to give time-resolved measurements of ventilation rates over long-term monitoring campaigns. Wallace et al. (2002) was noted to be an exception, but their use of pumped gas sampling techniques is likely too disruptive to be acceptable to most occupants. As discussed through Chapter 2, ventilation rates are variable over time, depending on weather conditions and occupant actions, so the method developed for this research was designed to be applied in a long-term monitoring campaign in order to reflect this variability. Section 3.2.1 discusses the ventilation measurement method upon which this research is based, and Section 3.2.2 presents the experiments carried out in an unoccupied test house to explore the assumptions of the technique. Given that the aim was to apply the method over extended monitoring campaigns, it was necessary to develop robust, systematic and efficient algorithms to identify and analyse appropriate periods of data, Sections 3.2.3 and 3.2.4 discuss the algorithms developed for this work in more detail.

3.2.1 Ventilation measurement using the CO_2 decay method

A tracer gas method will be used for this research as these are viable for time-resolved ventilation measurement. As discussed in Section 2.2.3.2 many gases have been used as tracers for ventilation rate research. Passive tracer methods using perfluorocarbons will not give temporally resolved measurements so are not suitable for this research. SF_6 has been commonly used in concentration decays, but due to its high GWP and restrictions on its use, it is not suitable for this work. However, CO_2 does not have these issues and has the advantage of being measurable using relatively inexpensive non-dispersive infra-red (NDIR) sensors. It is also naturally present in the atmosphere and using metabolic CO_2 as the tracer gas removes the need for artificial injection of tracer gas altogether (and negates the global warming concern attached to the previous two gases). Penman (1980) developed the use of metabolic CO_2 as a tracer gas on the grounds that this may be more acceptable to building occupants than the injection of unnatural tracer gases, this is an advantage in the context of this research particularly given its longitudinal nature. For these reasons, CO_2 has been selected as the most suitable tracer gas for this research.

As discussed in Section 2.2.3.3 there are several tracer gas techniques. The use of metabolic CO_2 as a tracer gas in occupied homes over an extended monitoring period has implications that were considered in choosing which technique to apply. In Section 2.2.3.3.3 it was noted that standard assumptions about metabolic generation rates of CO_2 can lead to significant uncertainty when these are used in the analysis of ventilation rates. Moreover, Sharpe (2019) argues that we must be more aware of the ethical aspects of post-occupancy research in buildings, and there is an ethical dimension to consider with respect to the use of occupant CO_2 generation for ventilation research. It is common to apply these methods overnight and in analysing the CO_2 generation rates it would become necessary to know or estimate each night how many people are present in the dwelling and the time that they sleep. This consideration for the privacy of the occupants, particularly over an extended monitoring period, is not balanced by the insights gained given that the results would be highly uncertain and alternative techniques can be used. For these reasons, neither the equilibrium nor build-up techniques were selected for this work.

Metabolic CO_2 can be used with the concentration decay technique as discussed in Section 2.2.3.3.2, as long as the zone of interest is unoccupied (and there is no air leakage to other zones). There are two important implications of this. Firstly, there has been little discussion of the identification of suitable unoccupied periods for CO_2 decay analysis in the literature; this will be explored further in Section 3.2.3. Secondly, the ventilation rate experienced by the occupant cannot be directly measured since the occupants cannot be present during the measurement period. As highlighted by Liddament (1996), a measured ventilation rate only characterises the measured space for the conditions in which it was measured. To address these issues, this study infers the likely ventilation rate experienced by occupants during different weather conditions and with different arrangements of doors and windows by recording these parameters. This facilitates an assessment of the extent to which the measured ventilation rates are likely to reflect the ventilation rates experienced during occupied times. The doors, windows, internal and external temperature were monitored, and the wind speed and direction were collected from the closest suitable weather station in the MIDAS (Met Office Integrated Data Archive System) database (Met Office, 2019) (further details are given in the case study description in Section 3.6.3).

The decay method provides a snapshot of the ventilation rate under the conditions of the measurement, so the length of a monitoring campaign is important. An extended monitoring campaign with repeated estimation of ventilation rate over time means that measurements can be taken under many different weather conditions in the dwelling as-configured by the occupants. This allows insights into the ways the occupants arrange the dwelling over time, thereby supporting the aim to study the ventilation in homes as-occupied and providing a link between the technical research and the social enquiry regarding the ways the occupants practice ventilation in their homes.

The following section presents the experimental work in an unoccupied dwelling to investigate aspects of the application of the CO_2 decay technique that would have been invasive to carry out in an occupied dwelling.

3.2.2 Exploring the ventilation measurement method in an unoccupied dwelling

A series of controlled experiments were carried out in an unoccupied dwelling to test aspects of the implementation of the CO_2 decay method. These included:

- The spatial homogeneity of CO_2
- The single zone assumption
- The effect of external CO_2 concentration variation

These are discussed in more detail below, but taken together the analysis at the test house helped to assess the uncertainties and limitations associated with the ventilation measurement using almost exactly the same equipment as used in the occupied dwellings. Additionally, these experiments provided appropriate data for developing analysis code in Python to handle the data from the occupied dwellings.

For several reasons the majority of measurements in the unoccupied test house were carried out in individual rooms. Practically, the unoccupied test house had high air permeability and a large volume (15.1 $m^3m^{-2}h^{-1}$ and 240 m^3, full details of the dwelling are given in Section 3.6.1), which meant a large amount of CO_2 was required to conduct whole-dwelling ventilation rate measurements. Additionally, taking measurements in individual rooms meant that impact of possible occupant actions, such as door opening, trickle vent use and curtain use could be explored in individual rooms with fewer variable factors than if such experiments had taken place in the whole dwelling. These experiments are discussed further in Section 3.3.

The spatial homogeneity of CO_2 in the rooms was investigated. As discussed in Section 2.2.3.1, a key assumption of the tracer gas method is that the tracer is well mixed in the measured space. The main measurement room was equipped with four CO_2 sensors so that differences between build-up of metabolic CO_2 without mixing fans and controlled release of CO_2 with mixing fans could be compared in terms of the resulting spatial inhomogeneity.

The individual rooms were treated as single zones, and the appropriateness of this assumption was explored. CO_2 sensors were also placed in all other rooms except the upstairs and downstairs hall so that the leakage of CO_2 from one room to another could be assessed.

Finally, external CO_2 is not usually measured with the same temporal resolution as the indoor CO_2 or at the same location as the measured space. Previous authors have taken different approaches to outdoor CO_2 measurement, from averaging external CO_2 measured somewhere else in the same city or at the measurement site, measuring a one-off value or using periods of unoccupied data to estimate external CO_2 (Guo and Lewis, 2007; Bekö et al., 2010; Sharpe et al., 2014; Cardoso et al., 2020). All the above authors assumed outdoor CO_2 was constant during their ventilation measurement periods.

The author has been unable to find any publications addressing the effect of variation of external CO_2 over time on ventilation rate measurements using CO_2 tracer methods. Initially it was intended to measure external CO_2 at the beginning and end of the measurement period at the unoccupied test house as recommended by Persily (1997), however it soon became apparent that the external CO_2 was varying considerably over the extended monitoring period. Indeed, Carrilho et al. (2016) has developed a technique for measuring ventilation rate which rests upon the diurnal variation of CO_2 due to photosynthesis, finding a variation of over 100 ppm over a day. As a result, measuring the external CO_2 before or after the measurement period does not necessarily reflect the external CO_2 concentration during ventilation measurements, particularly as this method was applied over an extended monitoring period and measurements could take place at any time during which the dwelling was unoccupied. The external CO_2 was therefore monitored continuously outside the test house (and later outside the occupied dwellings), which meant that the external CO_2 measurement was used in the calculation of CO_2 difference for each ventilation measurement. The precise handling of the external CO_2 was influenced by the results of this analysis. This is presented in Chapter 4 along with the rest of the results regarding the measurement method development.

3.2.3 Developing an occupancy algorithm

Guo and Lewis (2007) suggest that the difficulty in accurately determining when a dwelling is occupied is one of the reasons that there are few examples of the use of metabolic CO_2 as a tracer gas in the literature. Guo and Lewis (2007) identified decay periods using an occupant-reported daily log-sheet; however occupant diaries may not always be accurate and they increase the burden of the occupant participating in the research (Bryman, 2004). Roulet and Foradini (2002) monitored a single office-room and manually identified periods of decaying CO_2, implying that prolonged periods of decreasing CO_2 can be interpreted as indicating that there were no occupants present. However, this does not account for the possibility of leakage between zones and manual identification of unoccupied periods is a laborious process for long monitoring campaigns.

While there are few examples in ventilation measurement literature, there is much literature on determining building occupancy more generally. Chen et al. (2018) reviewed the literature on methods for determining occupancy and found a wide variety of sensors have been used including: PIR (passive infra-red), smart meters, CO_2 concentration alone and in combination with other environmental sensors, cameras, WiFi, BLE (Bluetooth low power) and others. These sensors have associated issues, for example: cameras can provide accurate data but bring privacy concerns, may not be accurate in low light conditions and often require significant computational complexity in analysis; smart meters may be non-intrusive for the occupants, but the association between power use and occupancy is not straightforward; WiFi signals are often available in indoor environments and have been used to estimate the number of and location of smart phones, however to translate this to occupancy it is assumed that occupants have one WiFi-enabled smart phone each, which may not always be the case. For the present research, it is convenient to base the occupancy algorithm on the use of CO_2 data since this will already be monitored for the ventilation measurement method.

Machine-learning algorithms have been developed to infer occupancy from CO_2 data (Lam et al., 2009; Worner et al., 2014; Szczurek et al., 2016). However, these methods rely on training periods during which occupancy must be monitored and it can be unclear how well the training data maps on to subsequent periods. This may be particularly important for long-term applications, such as in this research, since conditions may change significantly with the seasons. Additionally, in the context of this study, requiring the occupants to record the periods of their presence would add burden to participating, and be subject to reporting uncertainties (Bryman, 2004).

Methods for estimating the number of occupants using metabolic CO_2 have been developed using the mass balance equation (Wang and Jin, 1998; Wang et al., 1999; Sun et al., 2011; Parsons, 2014; Calì et al., 2015). These methods require an assumed occupant CO_2 generation rate as well as a ventilation rate. This is inappropriate for this research since the purpose is to measure the ventilation rate.

Naghiyev et al. (2014) identified several issues associated with using CO_2 to determine occupancy in dwellings, including:

1. Whether windows or doors are open or closed
2. The rise in a neighbouring room when the door between an occupied and unoccupied room is opened
3. The changing metabolic rate of occupants (either different occupants or different activity levels)
4. The specific circulation of air in a space and the measurement location
5. The frequency of movement between rooms
6. The reaction time of CO_2 sensors

Naghiyev et al. suggest that methods for determining occupancy from CO_2 data can be improved with knowledge of the infiltration rate of the dwelling, window and door opening data and knowledge of the airflow in the dwelling. Chen et al. (2018) found that best results are often obtained when different sensors are combined.

Some authors have included door or window opening into their methods. Dedesko et al. (2015) used beam-break sensors in an attempt to count the number of people passing in or out of the room. They also measured CO_2 concentrations and used estimated CO_2 generation rates to determine whether a beam-break event was associated with someone entering or leaving the room.

The research presented here does not require the determination of the number of occupants, only occupied and unoccupied periods need to be distinguished. Therefore in developing the method the focus was solely on techniques that improve the identification of occupancy. The above review has shown that CO_2 has potential for use in an occupancy algorithm, but additional sensors may help improve accuracy. As discussed above, the configuration of doors and windows is central to this research and this review of occupancy determination literature has suggested that door use data is useful for an occupancy algorithm, particularly for identifying the moment at which occupancy changes. As a result, a method for occupancy identification was developed using CO_2 concentration, door and window opening data.

The occupancy algorithm was part of the method used to measure ventilation rates in the occupied dwellings, but a detailed presentation of the algorithm is deferred until Chapter 4 because the development and testing of this algorithm are part of the results of this work. The algorithm was tested in an occupied case study dwelling which is described in Section 3.6.2.

3.2.4 Analysis algorithm

The analysis algorithm identified and analysed periods of decaying CO_2 concentration in unoccupied periods of data identified by the occupancy algorithm. Periods of decaying CO_2 concentration which met a series of empirically determined criteria were identified, the criteria included decay time, spatial homogeneity, and external CO_2 variation. These were used to calculate ventilation rates by fitting the data to the standard single-zone CO_2 tracer gas decay model, given by:

$$\Delta CO_2(t) = \Delta CO_{2,t=0} \exp(-At), \tag{3.1}$$

where $\Delta CO_2(t)$ is the indoor-outdoor CO_2 difference at time t after the beginning of the decay, and A is the air change rate. Compared to Equation 2.11 the concentration of tracer gas has been replaced by ΔCO_2 because the outdoor concentration of CO_2 is non-zero.

The results of the development of the analysis algorithm are presented in the following chapter (Section 4.2), where justifications for the criteria and thresholds used to determine which sections of data were used for ventilation rate analysis and their effect on the measured values are provided.

The uncertainty of a measurement 'characterises the dispersion of values that could reasonably be attributed to the measurand' (JCGM, 2008), where the measurand is the particular quantity subject to measurement. The uncertainty is influenced by the CO_2 sensors, the assumptions of the method and the definition of a ventilation rate as a measured quantity. The uncertainties associated with measurements of the ventilation rate are informed by the issues presented in Chapter 4, uncertainty calculation is presented in Section 4.3.

3.2.5 Summary

This section has described the research which took place to support the development of a method able to measure temporally-resolved ventilation in occupied homes. The method is based on the CO_2 decay technique, using metabolically generated CO_2. Metabolic CO_2 was selected as the tracer gas because it is naturally present in occupied dwellings, this reduces the amount of equipment required and thereby reduces the inconvenience of taking part for the occupant. Additionally CO_2 has a far lower GWP than many other commonly used tracer gases. The decay method was selected due to concerns over the accuracy of other tracer gas configurations when used with assumptions regarding metabolic CO_2 generation rates. Elements of the implementation of the CO_2 decay method were investigated in an unoccupied test dwelling, including spatial homogeneity of CO_2, the single zone assumption and the influence of external CO_2 concentration variation.

Since the method developed for this research was designed to be implemented in long-term monitoring campaigns in occupied homes, it was essential to develop robust, repeatable and efficient algorithms to identify and analyse appropriate sections of data. An occupancy algorithm was developed to identify unoccupied periods as these were required for CO_2 decay analysis. Additionally, an analysis algorithm was developed to identify and analyse periods during which the dwelling was unoccupied and the CO_2 concentration data was appropriate for tracer gas decay analysis. This selected periods of data based on empirically determined thresholds relating to decay time, spatial homogeneity and external CO_2 variation.

The items above were supported by additional measurements. These included measurements of temperature difference and the open or closed state of doors and windows, and Met Office (2019) measurements of wind speed and wind direction at a nearby weather station. These data allowed investigation into the effect of such parameters on the measured ventilation rates, and also allowed a comparison of the conditions during ventilation measurement periods and the conditions observed when occupants are present. Different elements of the method were tested in different case study dwellings, and the results of these analyses are presented in Chapter 4.

Having set out the approach to the ventilation measurement method, the following section discusses how this method was applied to evaluate the adequacy and variation of ventilation in occupied homes as experienced by occupants.

3.3 Ventilation rate research - adequacy of ventilation

The second part of this research relates to the adequacy of ventilation rates in case study homes and how this varies over time. However, there is no clear value for adequate ventilation, given that pollutant sources and strengths are building and time dependent (Salis et al., 2017), as discussed in Chapter 1. Nonetheless, ADF gives a whole-dwelling ventilation rate that should be achieved in newly built dwellings with the boost ventilation off and windows closed. This rate is dependent on floor area and number of bedrooms. The measured ventilation rates were compared to the ADF value in all cases. The ADF ventilation rates are given as volumetric flow rates (in l/s) but generally when converted to air changes per hour these are close to 0.5 ach, a commonly used threshold for adequate ventilation found in many European ventilation standards (Dimitroulopoulou, 2012). Section 2.3 presented the ventilation strategy in ADF in more detail.

Two streams of investigation contributed to this section of the work: a series of experiments were carried out in an unoccupied test house to investigate the effect of common occupant actions on ventilation rates, this is discussed in Section 3.3.2; measurements in occupied homes were carried out over an extended period to investigate the ventilation rates achieved in homes built in accordance with the current regulations, this is discussed in the next section.

3.3.1 A measurement campaign in occupied homes

This research is centred on understanding ventilation in occupied homes, this section describes how case study homes were investigated. These occupied case study dwellings were required to be built according to ADF (HMG, 2013b), so this allowed a comparison of the intended ventilation system and ventilation rates described in ADF and those observed in the occupied dwellings. Four flats with continuous MEV ventilation strategy (system 3 in ADF) were studied. Section 3.6.3 describes the recruitment and characteristics of these dwellings in detail.

To support the interpretation of the ventilation rate measurements several other parameters were measured. Flow measurements of the MEV system were carried out in each of the flats and compared to the flow requirements set out in ADF. Air permeability measurements in line with the ATTMA (2016) test protocol were carried out. Additionally, following the method set out in ATTMA (2016), an effective leakage area (ELA) was calculated for the trickle vents open and closed so that the additional ELA due to the open trickle vents could be calculated. While one of the dwellings was depressurised for air permeability measurements a thermal camera was used to investigate air leakage paths. Finally, the door undercuts were measured since ADF requires an undercut of 7600 mm^2 (10mm for a standard width door) to provide airflow throughout the dwelling if internal doors are closed (HMG, 2013b). Further details of these measurements are provided in Section 3.6.3.

The measurement method developed in the earlier part of the research was used to measure ventilation rates. Ventilation will vary with the seasons due to weather conditions and occupant behaviour, so the measurement campaign ran from June 2019 to January 2020 to capture some of this seasonal variability. The effect of temperature differences and wind on the ventilation rates was explored, as well as the effect of the configurations of internal doors and windows. Combining this data with the outcomes of the occupancy algorithm allowed a comparison of the conditions during occupied and unoccupied times, enabling investigation of the representativeness of the conditions during measurement times to the conditions during occupied times. This gave insight into the extent to which the occupants are likely to experience variable ventilation rates.

The ventilation rate research in the occupied dwellings took the form of a natural experiment: the ventilation was measured in the conditions in which the occupants arranged the dwelling. This is important for understanding ventilation performance in homes built to the current regulations in practice, as a system of building and occupants. Nonetheless, this meant that insights into the effect of using ventilation equipment such as trickle vents or closing doors were not necessarily observed. Some of these effects were investigated in an unoccupied test house, as discussed in the following section.

3.3.2 The effect of occupant actions on ventilation rates

The literature review highlighted that various occupant actions will likely affect the ventilation rates; for example closure of trickle vents, use of curtains and blinds and internal door closure. These effect of these actions were tested in an unoccupied test house to explore issues related to their use. Carrying out this research in an unoccupied dwelling allowed systematic investigation of the effects with known and controlled conditions without disturbing the occupants. It also provided an opportunity to pilot the methods and gain understanding of the impact of use of common technologies in homes. The available test house did not conform to current ADF standards and notably did not have any mechanical ventilation, so it was not possible to investigate any issues associated with such systems. Nonetheless, the test dwelling was typical of a large proportion of the English housing stock (Roberts et al., 2018), it is described in detail in Section 3.6.1.

An experimental research design was used for the investigation of trickle vent, curtain and door closure on ventilation rates. Full details of the experiments are given in Section 3.6.1. Clearly the weather conditions could not be controlled, so measurements were taken over several months with many different external conditions, which allowed the relationship between weather and ventilation to be explored.

In support of the ventilation rate measurements, other key characteristics of the dwelling were investigated. These included air permeability measurements conforming to ATTMA (2016) guidance, a qualitative investigation of air leakage paths using a smoke pen while the dwelling was pressurised and measuring the depth of the door undercut in the main measurement room. Full details of the data collected at the unoccupied test house are provided in Section 3.6.1.

In summary, unlike the studies carried out to support revisions to ADF (Crump et al., 2005; DCLG, 2009; MHCLG, 2019b), this part of the work is not an investigation of whether the studied homes are capable of reaching the ventilation rates required by ADF if they are used in accordance with the intent stated in ADF, but whether they achieve these rates *as used*. As part of understanding why the homes were or were not used in the manner set out in ADF, the ventilation practices of the occupants were investigated, the approach to this part of the research is discussed in the following section.

3.4 Social sciences research

Through the literature review it became clear that much ventilation research has put limited emphasis on the influence and interactions between the ventilation system and the occupants. The sections above have discussed the approach to the technical parts of the research, this section will address the social aspects. The final research question seeks to integrate an exploration of the social aspects of ventilation in this primarily technical piece of work: does the way ADF assumes ventilation will be carried out at home adequately capture actual ventilation practices? This question is clearly best addressed by a social research method.

The use of social practice theory (SPT) for interpreting the occupants' interactions with their home and how they affect the ventilation in their home will be presented first. Following this the choice of data collection method will be discussed and the method outlined. The qualitative analysis method will then be presented. Finally, the interview guides will be discussed along with the refinements made in the light of the practice interviews.

3.4.1 Social practice theory framework

Section 2.5 showed that social practice theory has been widely adopted by authors seeking to understand the role that people play in the use of energy in the built environment, for example Shove and Walker (2010), Gram-Hanssen (2010a), Behar (2016), Kuijer and Watson (2017), and Lowe et al. (2018). SPT places an emphasis on the interactions between the technical and social regimes in which we live. This is appropriate for this research given the interest in the ways occupants ventilate their homes compared to the ways ADF, with its primarily technical outlook, intends ventilation to happen. Additionally, the bulk of the research in this thesis is technical in nature so it is apt that the social dimension is able to stretch in this direction.

However, the exact formulation of SPT and the elements considered to make up social practices have varied between authors. The research presented here follows the SPT framework set out in Gram-Hanssen (2010a). The work set out in this thesis is primarily technical in nature and the SPT framework will be used in comparing participant practices with assumptions embedded in ADF, so it is helpful to follow a formulation of SPT which is pragmatic rather than oriented towards more theoretical considerations.

Gram-Hanssen's (2010a) framework closely mirrors Schatzki's (for example, in Schatzki, 1996; Schatzki, 2002; Schatzki, 2010), although the names of the elements have been adjusted and expanded. Gram-Hanssen (2010a) includes **products, things and technology** as a fourth element. This means that the technologies specified in ADF (continuous MEV, trickle vents, windows, doors etc) can be explicitly included within the analysis framework as well as other technologies which the participants might use (for example, air fresheners), which is useful for the current research. Gram-Hansen also expands Schatzki's rules element to include knowledge and language. In Gram-Hanssen (2010b) and Bartiaux et al. (2014) this element is strictly interpreted as **formal or institutionalised rules and knowledge**, such as knowledge of energy use from energy bills or from government guidance. However, in Gram-Hanssen (2010a) this element is loosened such that it includes tacit, implicit and 'folk' knowledge. Since this part of the work is framed around ADF and how participants' practices compare to the intended actions within that document, it is appropriate to maintain a stricter definition of formal and institutionalised knowledge so that greater emphasis is placed on the role of formal channels of information dissemination and regulations. The **practical understandings** element is expanded to include embodied habits and know-how in Gram-Hanssen (2010a). This element is about 'knowing what to do, and knowing how to identify and react to something' (Gram-Hanssen, 2010a, p. 177). In terms of ventilation in the home, we can understand this element as being related to knowing how to identify circumstances which indicate that something needs to be done to affect the air in the home, and what to do about this. Finally, teleoaffective structures are renamed **engagements and meanings** in Gram-Hanssen (2010a), this element is about the aims and goals of the practitioners. ADF outlines the purposes of different types of ventilation in the strategy it presents, these purposes can be interpreted as corresponding to the meanings element of a practice. Further specific discussion of the translation of ADF into the SPT framework is deferred until Chapter 6 in which the results of this part of the work are presented.

3.4.2 Social data collection method

The main focus of the enquiry related to the participants' ventilation practices; the things they did in their homes which are likely to affect ventilation or likely to affect indoor air quality and therefore affect the amount of ventilation required. Since the physical environment of the home was of interest to the research it was advantageous to be present in the dwelling with the participant at the time of their answering the questions. Also, Behar (2016) has shown that participants sometimes find topics around ventilation confusing, and Sharpe et al. (2015) showed that not all participants recognise the names of ventilation equipment (e.g. trickle vents). Additionally, according to Walliman (2006) visual clues from the interviewee during face-to-face interviews (such as smiling, nodding, looking puzzled) can help the interviewer to judge the interviewee's understanding of the question and meaning of their responses.

Since the focus was on comparing the participants' practices to the design intentions and assumed occupant actions within ADF, the range of topics to be covered were fairly well defined. These included the participants' use of the technologies referenced in ADF including windows, doors, trickle vents and fans, as well as other technologies not specified in ADF which the participants used to affect the air (e.g. air fresheners); the circumstances in which these technologies were used and how they were used were of interest. The participants' views about indoor and outdoor air quality needed to be explored as these are directly related to the need for ventilation in homes from a technical perspective, additionally the literature review (Section 2.5.2) identified that perceptions of air quality influence ventilation practices. This suggested that an unstructured interview approach, in which broad themes are covered and participants are fairly free to direct the topics covered (Gubrium et al., 2012), would have been inappropriate as specific topics may have been missed. At the other extreme, structured interviews follow a standard format for each participant (Gubrium et al., 2012), this method was used by Sharpe et al. (2015) to give a helpful indication of the proportion of respondents opening trickle vents and windows for generic reasons (too hot, smells, noise, etc). However, previous research has already shown that people have a wide range of sometimes surprising reasons for their ventilation behaviour (e.g. Behar (2016) found that a fear of spiders prevented some participants from opening windows). Moreover, SPT emphasises the interconnectedness of the various elements of practices and of other practices woven into the experience of daily life; so a structured approach would not be appropriate for addressing these kinds of issues. Semi-structured interviews are a qualitative interviewing method in which a fairly fixed set of questions is asked, but where the interviewer is free to ask follow-up questions or vary the order of questioning depending on the responses of the interviewee (Kvale, 2011). This allows qualitative data to be collected on fairly focused topics, but allows unexpected answers and ideas to be followed-up, and is therefore appropriate for this research seeking to understand the participants ventilation practices.

The interviews were combined with a walk-through in which the participants showed the author around their home. Walk-through interviews can help the interviewees to recall contextual habits or information, and help the interviewer to understand the physical arrangements and context for the information being given, they can be particularly helpful when the topic is related to everyday or routinised actions (Chiu et al., 2014). Additionally, interviewing in the home allows technologies and their use to be demonstrated within the interview context (Pink et al., 2017). Additionally, specific arrangements, products or things relevant to the ventilation could be raised by the interviewer even where the interviewee may not have known this was a relevant artefact. This helped to align the social data with the technical part of the research as the physical arrangements relevant to ventilation could be noted by the interviewer and then raised in relevant terms for the participant.

Formulation of the pilot interview guides and the alterations following the practice interviews and analysis are discussed in the following sections.

3.4.3 Interview guides

Interview guides for semi-structured interviews give an outline of the topics to be covered and may give suggested questions (Kvale, 2011). Interview guides were created for a set of pilot interviews and refined for the final set of interviews. The interview guides were structured into four broad sections. Following the advice in Kvale (2011) the interviews began with a briefing in which participant consent was confirmed, the use of the voice recorder was agreed upon, the scene was set and an outline of the topics to be covered was given. The initial questions were designed to settle the interviewee and interviewer by gathering relevant background context, such as how long the interviewee had lived in the current flat and what their previous home was like. More specific questions about the home were then asked, initially about how the temperature is in summer and winter, since temperature is potentially a more tangible and more frequently discussed concept than ventilation. The main part of the interview followed with questions about air and ventilation. In closing the interview, participants were asked if they had further reflections on the home they wanted to share, and if they had questions for the interviewer.

The section of the interview relating to ventilation and indoor air quality was structured around several key themes. Perceptions of air, including aspects such as condensation and smells (including those deliberately introduced into the home such as scented products), which are clearly related to ventilation and air quality, but which may not necessarily come to mind when asked about air and air quality, were discussed first. Questions were then broadened to ask about perceptions of the air throughout the house, in this way hoping to draw out information about how the perception of ventilation or air quality may vary across the home. Throughout the interview the participants were asked if their responses would vary between rooms, at different times of day and in different seasons. Section 2.5.2 noted that previous research has found that practices related to ventilation can be influenced by a wide variety of variable factors, such as weather, season and the performance of other tasks. Additionally, the ventilation strategy described in ADF refers to the locations and frequency with which pollutants are produced and need to be ventilated, ADF also makes a brief reference to the effect of warmer weather on using windows for thermal comfort. Moreover, the physical component of this project was concerned with the variability of ventilation, so this temporal and spatial aspect linked the technical and social research. The participants were also asked about the overall quality of the indoor and outdoor air. In the final part of this section the occupants were asked to explain their perception of how the ventilation system worked.

The interview then continued during a walk-through, in which the physical arrangements were observed, fans, windows and doors were discussed and the circumstances in which they would be used were raised. The participants were asked about the maintenance of the ventilation equipment and whether advice had previously been given about the use of the ventilation equipment. Finally, the interview was drawn to a close by asking the participants if they had any more comments, or any questions for the interviewer.

Given the semi-structured nature of the interviews, it was uncommon for the interview guide to be followed exactly: participants often pre-empted questions, or began answering a question on one topic and went on to talk about other related issues that appeared at different points in the interview guide. The ventilation technologies in particular (windows, fans and doors) were always discussed prior to the walk-through. However, this meant that during the walk-through clarifications could be sought by the author, and opportunities for further reflections were provided.

3.4.3.1 Practice interviews and refining the interview guides

It is useful to carry out practice interviews to test interview guides and reflect on whether the guide elicits responses which address the research questions (Braun and Clarke, 2013). Three practice interviews took place in August 2019. These participants had responded to a recruitment letter to take part in the whole research project including the physical monitoring. This research aimed to study dwellings built in line with ADF (HMG, 2013b) and with MEV and trickle vents. The development in which these participants lived had been identified as appropriate for this project by the building developers, but upon installing equipment in these dwellings it became apparent that they had an MVHR system and were therefore unfortunately inappropriate for the study (see Section 3.6.3). Nonetheless, these participants were willing to take part in the practice interviews. Despite having a different ventilation system to the final set of occupied dwellings the general topics were still relevant, and conducting the practice interviews with these participants gave an opportunity to trial the interview guide with members of the public.

The practice interviews were a useful experience in keeping track of which questions or topics have been covered, and deciding which aspects of the participants' responses to follow up. In analysis of the practice interviews, several areas for improvement were identified. For example, in the practice interviews longer silences could have been left while the participants thought about their answers, and it would have been useful to clarify the use of particular words. The practice interviews allowed period of reflection on these issues so that they could be addressed before the final interviews took place.

The final interview guide was modified to reflect the insights gained through analysis of the practice interviews. The original interview guide avoided directly using words such as 'stuffy' in order avoid influencing the participants' descriptions of the air, but all the participants used this word spontaneously when describing various aspects of their perception of the air (e.g. 'if it gets a little stuffy we might open [a window] to let a little air in'). As a result, 'stuffy' was included as a possible prompt, for example if the participants were unsure how to answer a question on their perception of the air they could be prompted by giving possible qualities of the air including 'stuffy', 'fresh', 'humid' and 'smells'.

The original guide asked about their previous home and differences compared to their current home as a way to settle in to the interview. However, through the practice interviews it became apparent that further references to previous homes can be helpful for explaining why they take certain actions in their current homes. For example, all the participants found it difficult to explain why they tended to leave internal doors open, but in one of the practice interviews the participants referred to their previous home:

JESSICA I wonder if you could say anything more about why you like to keep the [internal] doors open the rest of the time?

BETH Gosh... (*laughs*)

BEN I don't know really! I don't, yeah, um are we lazy? I don't know, why do we do that?

(*Ben and Beth discuss previous home*)

BETH ... whereas here, you don't feel a draught, so you don't feel any need to shut the doors really.

In this example, by referring to a previous home in which their actions were different the participants were able to reflect on why their behaviour had changed in the new home. This relates to Hauge (2013) and Royston (2014), who find that experiences of previous homes can significantly affect the way people perceive and interact with their subsequent homes. For both of these reasons, the revised interview guide gave more opportunities for discussion about previous homes. Additionally, when participants struggled to answer questions a strategy used in the final interviews was to ask about experiences in previous homes or other buildings.

The revised interview guide included a greater variety of prompts for eliciting reflections on perceptions of the air and its various characteristics (including temperature, humidity, smells, and air quality). The original guide included direct questions about the perceptions of the air in general (as well as specifically about IAQ and outdoor AQ) and perceptions of phenomena which could indicate low ventilation rates, such as condensation and cooking smells and whether these linger or travel around the home. However, the practice interviews returned a wide variety of other ways in which the air became apparent for the occupant. Notably, all the participants referred to the moment of entering the home as an instance at which the air became apparent to them. This is perhaps not surprising as occupants become accustomed to air quality in a space, so are more conscious of it in the first moments after arriving in a new space (Persily, 1997). The participants also referenced the survival of plants over extended periods, the presence of dust, a lack of mould and perceptions of sound insulation in relation to the air quality and air flows in their homes. This significantly increased the range of air-related perceptions compared to those initially envisaged. Royston (2014) investigated the ways that people become aware of heat flows in the home, she found that sensory perceptions of sight (seeing a curtain move due to cold air from outdoors or seeing the flickering of a candle), sound (hearing boilers coming on or radiators tapping), smell (smell of a cold, damp room or of a radiator heating up) and touch (feeling the resistance of butter left out of the fridge) could all be involved. In this way Royston highlights how different senses can be involved in the perception of an invisible and ephemeral phenomenon. As a result, the revised interview guide included more space for eliciting the ways in which ventilation or air became apparent to the participant.

The final interview guides are given in Appendix B.

3.4.4 Qualitative analysis method

All interviews were recorded and transcribed verbatim. The transcription process can be an important part of the analysis as this provides an opportunity for the researcher to become familiarised with the data (Merriam and Tisdell, 2015). Following the transcription, analysis took place using Nvivo as a tool to manage the data.

Merriam and Tisdell (2015, p. 207) describe qualitative analysis as "a dialectic in which you move between seeing the big picture (the 'forest') and the particulars (the 'trees') ". The analysis was an iterative process, and involved several cycles of in depth analysis of the interview transcripts followed by 'zooming-out', considering the wider research agenda and consulting and critiquing the literature. Through this process, common themes began to emerge.

The interviews were firstly coded according to the Gram-Hanssen SPT framework, which was discussed in Section 3.4.1. Coding is a process of assigning a shorthand designation to relevant bits of data so that they can easily be retrieved (Merriam and Tisdell, 2015). Relevant sections of the interviews were assigned codes relating to the four elements of the SPT framework as appropriate. These sections of data were further assigned short codes giving more detail to the specific element. For example, under the 'practical understandings / embodied habits' element, sections of data were also assigned to codes such as 'opening windows', 'opening doors' or 'what to do for stale air'. This further coding allowed an overview of the ideas involved in each of the elements to emerge.

Several memos were made to keep track of ideas emerging throughout the analysis process (Merriam and Tisdell, 2015). For example, one memo recorded the emergence of common themes, another recorded sections of the data which did not naturally fall into the SPT or ADF frameworks but which were relevant to the ventilation conditions, another summarised and compared the responses between participants. During the analysis of the pilot interviews, a memo keeping track of aspects of the interviewing technique which could be improved in the final set of interviews was used whenever the analysis pointed towards areas that could be improved (e.g. seeking clarification over the use of particular words).

After several rounds of in-depth reading of the transcripts, comparing findings with published literature and considering the emerging findings in the context of the wider research project, common themes emerged. Themes are developed to help tell a richer, more detailed story about the data (Braun and Clarke, 2013). Emerging themes were recorded in a spreadsheet, with short extracts from the interviews which contributed to those themes. Links to ADF, the literature and to the technical findings from the other parts of this research were also recorded in this spreadsheet. Themes are developed in relation to the research question (Braun and Clarke, 2013), so the themes in this work make reference to the similarities and differences between the participants' practices and the assumptions in ADF.

3.4.5 Summary of the social research approach

This section has described and justified the approach to the social research conducted for this thesis. Semi-structured interviews and walk-throughs were conducted with the residents of the occupied dwellings in which the extended physical monitoring also took place. These interviews aimed to elicit insights into the ways the occupants interacted with their homes that influenced ventilation (whether or not they intended to affect ventilation). The interviews covered topics such as doors and windows, temperature and indoor air quality from an everyday perspective. The interviews were transcribed and analysed using the SPT framework set out in Gram-Hanssen (2010a). This data collection and analysis gave insights into the ways that the ventilation equipment has been incorporated into the participants' ventilation practices, and how these relate to the intentions and assumptions in ADF (HMG, 2013b).

This section concludes the descriptions and justifications of the research methods used in this project. The following section reviews the research ethics, followed by details of the case studies used in this research including the measurements and data collected at each case study. Following the description of the case studies, a summary and overview of the research methods will be given.

3.5 Research ethics

This research was carried out with approval from appropriate UCL ethics boards for all aspects of the research taking place in occupied homes, and the project was compliant with the General Data Protection Regulation.

The participants provided their informed consent to take part in the study after reading an information sheet with a plain English explanation of the data that would be collected if they agreed to participate. The information sheet also clearly explained what would be known from the data, including that the CO_2 data would indicate when their dwelling was occupied but that the actions and movements of the occupants were not of interest to the research. The information sheet emphasised the lack of obligation to take part and the channels available for withdrawing from the study and lodging any complaints arising as a result of the research. If the participants agreed to take part in the research they signed an informed consent form to indicate that they had read and understood the information sheet. The information sheet and informed consent form are given in Appendix A.

There were some benefits to the participants from taking part in the research. Following completion of analysis, the participants were offered a plain English explanation of the findings and advice about maintaining good indoor air quality and ventilation in their homes. Additionally, the participants were offered a £25 gift voucher as an expression of thanks for taking part in the research.

The research was designed to do no harm to the participants or the researcher. Risks to physical harm were addressed and mitigated through the completion of appropriate risk assessments, which were completed prior to visiting the dwellings. Risks to reputational harm to the participants was mitigated by ensuring that the participants were non-identifiable in the presentation of all results from the project.

3.6 Case study sites and data collected

This research made use of several different case studies. This section describes the characteristics and data collected for of each of these case studies. The occupied dwelling in which the occupancy algorithm was tested, referenced in Section 3.2.3 is described in Section 3.6.2. Details of the four occupied dwellings where the extended monitoring campaign and interviews were carried out are given in Section 3.6.3. The next section describes the unoccupied test house.

3.6.1 Unoccupied test house

An unoccupied test house (UTH) was used to test the CO_2 tracer gas decay method for ventilation measurement and investigate the effect of actions such as trickle vent, curtain and door use as described in Sections 3.2.2 and 3.3.2 respectively. Measurements were taken between August 2018 and February 2019. The next section physically describes the dwelling and the section following this describes the measurements taken in this dwelling.

3.6.1.1 Physical description

The UTH was one of the Loughborough Matched Pair of 1930s Semi-detached test houses which are operated by the Building Energy Research Group (BERG) in the School of Architecture, Building and Civil Engineering at Loughborough University. The dwelling has uninsulated suspended timber floors, uninsulated cavity walls and has been retrofitted throughout with double glazing and trickle vents. The dwelling has a floor area of 95 m^2, and a volume of 240 m^3. Semi-detached dwellings are the most common housing type in the UK, the floor area is similar to the UK mean, and 16.7% of UK dwellings were built in the 1930s (Roberts et al., 2018). This house is therefore representative of a large proportion of the UK housing stock. Figure 3.1 shows the front of the test house.

The dwelling is naturally ventilated with no mechanical ventilation. The total geometric area of the trickle vents was 32,000 mm^2 for the whole house and 6,400 mm^2 for the back room. The geometric area is provided because the slots inside the trickle vents were cut smaller than the manufacturer recommended, so the equiv-

Figure 3.1: Outside the Loughborough Matched Pair test house.

alent area is not known. If the dwelling were newly built, background ventilators with equivalent area of at least 5,000 mm^2 would be required in the single room, and 45,000 mm^2 in the whole house.

Two air permeability tests were carried out following ATTMA guidance (ATTMA, 2016), all trickle vents were closed. Measurements were taken with a Minneapolis Model 3 and a Retrotec 6000 blower door on calm weather days in August 2018 and February 2019 respectively; one pressurisation and depressurisation test was carried out on each occasion. The measured air permeability at 50 Pa was 13.9 m^{3}m^{-2}h^{-1} in August 2018 and 16.3 m^{3}m^{-2}h^{-1} in February 2019. The dwelling was tested in the same configuration for both tests and reasons for the discrepancy are not known. Previous studies have suggested that in newly built dwellings the effect of 'drying out' after construction may be associated with an increase in air permeability particularly where mastic has been used to seal air leakage paths (Stafford et al., 2014), but the present dwelling had not been recently refurbished so this is not a likely cause of the difference. Further studies have identified seasonal differences in air permeability (Mélois et al., 2019) but this effect has not been well characterised for all building types. For the purposes of characterising the dwelling for this research the mean of the two values, 15.1 m^{3}m^{-2}h^{-1}, is used.

This issue highlights the value of longitudinal studies.

A qualitative smoke pen investigation of air leakage paths was carried out while the dwelling was pressurised for an air permeability test. This revealed several significant air leakage paths: in the under stairs cupboard, around the services in the kitchen and bathroom, through several cracks in the walls and around the front door. The windows were well sealed. The location of these leaks is fairly common (Stephen, 2000).

The main measurement room door, the back room in Figure 3.2, had an undercut with depth 6 mm and area of 4560 mm^2. This is significantly smaller than the 7600 mm^2 undercut required for new dwellings according to ADF (HMG, 2013b).

3.6.1.2 Description of equipment used and data collected

Figure 3.2 shows the floor plan of the UTH and indicates location of sensors. All indoor sensors were Eltek GD47 sensors, a device which combines CO_2 concentration, temperature and humidity measurement. Indoor sensors were installed in August 2018. A battery operated HOBO MX1102A sensor measuring CO_2, temperature and humidity was installed in an outdoor utility room of the neighbouring house (also unoccupied) at the beginning of November 2018.The door to this utility room was poorly fitting and it has been assumed that the air change rate in this space was high enough that it represents the outdoor CO_2 concentration. These devices all collected data at 5-minute intervals. The measurement ranges and accuracy of these instruments are given in Table 3.2. The Eltek GD47 data sheet stated a temperature dependence of 2 ppm /° C. Due to the lack of controlled CO_2 environments no attempt has been made to determine the influence of this dependence on the measurements taken in this thesis. Additionally, the data sheet for the sensor states a pressure dependence of 0.14% /mbar deviation. The indoor and outdoor sensors will be exposed to different pressures, however a CO_2 deviation of 0.1% would be expected with a pressure difference of 70 Pa; a pressure difference this large is unlikely to be experienced in a dwelling and the deviation is small so the pressure dependence is likely to be negligible and has been ignored hereafter.

HOBO UX90-001M state loggers with magnetic relays were installed on the

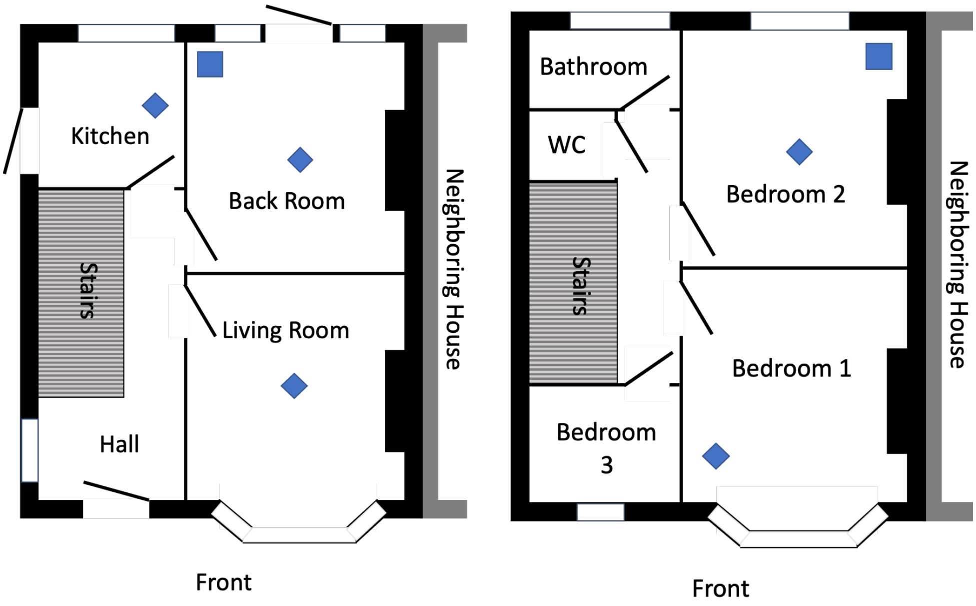


Figure 3.2: Layout of the test dwelling: ground floor on the left hand side, first floor on the right hand side. The CO_2 sensors which were in place throughout the monitoring period are indicated by the blue diamonds, these were located between 1.1 m and 1.3m above the floor. During the single room tests in the back room, three further CO_2 sensors, represented by the blue square, were located at floor level, at ceiling level and 1.2 m above floor. During single room measurements in Bedroom 2, two further CO_2 sensors, represented by the blue square, were located 1.2m above floor and at ceiling level.

Table 3.2: Measurement ranges and stated accuracies of the sensors used in the case study dwellings.

Sensor	Measurement Range	Stated Accuracy
Eltek GD47 - CO_2 concentration	0 to 5000 ppm	50 + 3% measured value (ppm)
Eltek GD47 - Temperature	-5 to 40 °C	0.4°
Eltek GD47 - Relative Humidity	10 to 90%	2%
	90 to 100%	4%
HOBO MX1102A - CO_2 concentration	0 to 5000 ppm	50 + 5% of measured value (ppm)
HOBO MX1102A - Temperature	0 to 50 °C	0.21 °C
HOBO MX1102A - Relative Humidity	20 to 80%	2%
	0 to 20% ; 80 to 100%	6%

front, back room, bedroom 2 and back doors at UTH. These sensors recorded the time and the open/closed state of the door every time the door was opened or closed (event-logging). The sensors recorded the door as open when the distance between the sensor and magnet was approximately 2 cm. These sensors were installed so that an exact record of the time that the test house became unoccupied or occupied could be inferred in addition to manual record keeping of experiments and times the researcher was present and absent. Additionally, this meant that if UTH was occupied by people other than the author (e.g. the Loughborough University security team) then this would be known and CO_2 data during this period would not be analysed.

Unfortunately, the state loggers' internal clocks drifted. This was observed in the data where manual records showed that UTH became occupied at a particular time, but the door sensors recorded an impossible scenario where the door to the back room opened shortly before the front door opened. This meant that the back room door sensor's internal clock ran slightly faster than the front door sensor's internal clock. During the course of the campaign the time discrepancy worsened. As a result, the time data from the back room was adjusted (by adding a linearly increasing offset to the recorded time) such that the front door always opened first when the dwelling was known to be becoming occupied from the manual records.

Weather data were extracted from the Met Office MIDAS data set (Met Office, 2019). A weather station located on the outskirts of Loughborough approximately 5 miles from the test house which recorded hourly temperature, wind speed and wind direction was used. Wind speed is reported to the nearest knot, and wind direction is reported in 10° increments. External temperature was measured in the garden of the UTH, these data were recorded every minute[1].

3.6.1.3 Experiments

To measure the ventilation rate using the CO_2 concentration decay method the CO_2 concentration was raised and then allowed to decay. The CO_2 concentration was raised either using metabolically generated CO_2 (in which case the author was

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[1] This data was very kindly shared by Virginia Gori, who collected it for a different project.

present in the measurement room for approximately 1 hour to raise the CO_2 concentration) or with a release of CO_2 from a pressurised gas cylinder. Following the build-up of CO_2 the dwelling was left unoccupied for at least 75 minutes to allow the CO_2 concentration to decay.

Measurements were taken to explore the whole house and single room ventilation rates. Two rooms were independently used for single room experiments, the room in which the majority of the single room measurements took place is referred to as the ‘back room’ on the ground floor in Figure 3.2, the second room is referred to as ‘bedroom 2’. Four CO_2 sensors were placed in the back room to explore the uncertainty introduced due to spatial inhomogeneity.

The single room and whole house experiments had slightly different experimental base case conditions, Table 3.3 shows which base case conditions were varied for experiments in the different spaces. For the single room the base case was open trickle vents throughout the dwelling, open curtains, metabolic CO_2 release, mixing fan off, door to measurement room closed and all other internal doors open. The trickle vent and curtain experiments in the single room were designed to investigate the effect of possible occupant actions on ventilation rates. The effect of spatial inhomogeneity was also investigated in the single measurement room by comparing the base case to an identical configuration, but with mixing fans were switched on.

For the whole dwelling the base case was open trickle vents throughout the dwelling, open curtains, controlled CO_2 release, mixing fans on and all internal doors open. Whole dwelling experiments used controlled release of CO_2 due to the impossibility of one person adequately dosing and mixing sufficient CO_2 in a large house with metabolic CO_2. Mixing fans were used since the controlled release gave small point sources of gas which needed to be dispersed throughout the whole dwelling. One measurement took place with trickle vents closed and one with trickle vents open. These measurements took place in January and February 2019. Over 130 ventilation experiments were carried out in various configurations.

Table 3.3: Configurations of ventilation experiments in different spaces at UTH.

Test condition	Back room	Bedroom 2	Whole House
Base case	√	√	√
Trickle vents closed	√	√	√
Curtains closed	√	×	×
Rest of dwelling trickle vents closed and doors closed	√	×	×
Controlled CO_2 release, mixing fans on, trickle vents open and closed	√	×	×

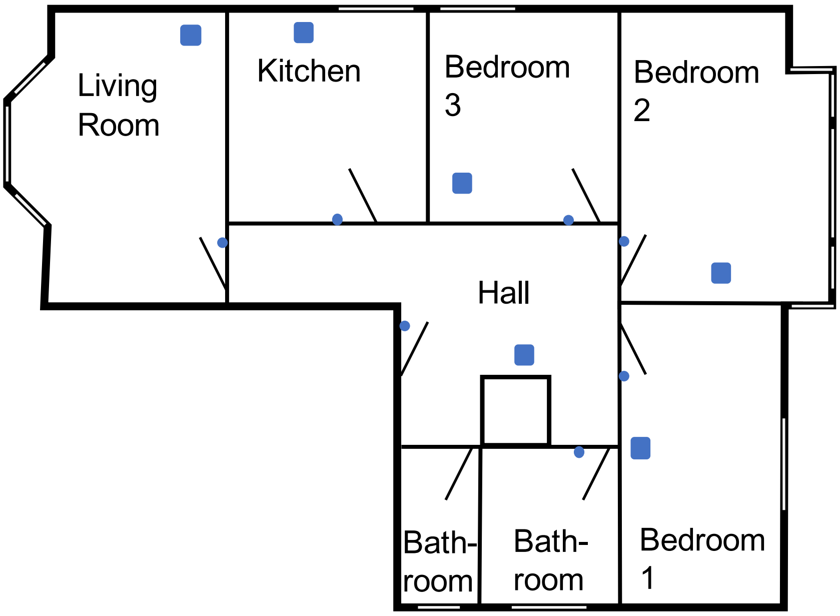


Figure 3.3: OAF floor plan and location of sensors. Eltek GD-47 sensors monitoring CO_2, temperature and relative humidity are indicated by blue squares, proximity sensors on doors are indicated by blue circles.

3.6.2 Occupied dwelling for developing occupancy algorithm

A monitoring campaign was set-up in the author's flat, henceforth referred to as OAF (occupancy algorithm flat), to provide data for developing the occupancy status algorithm. OAF was the upper ground floor of a house built in the late 1800s and was naturally ventilated. OAF was monitored between February and July 2018, three adults lived in the flat and it was unoccupied for several hours most days as all the occupants worked full-time.

As discussed in Section 3.2.3, the main parameters of interest for the occupancy algorithm were CO_2 and door use data. CO_2 was measured using Eltek GD47 sensors (as above), these were placed in every room except the bathroom due to the requirement for mains operated power supply and the safety risks associated with electrical equipment in bathrooms. These sensors recorded data every five minutes. Eltek GS34 State transmitters with magnetic sensors for recording open/closed state were used on all internal doors except one bathroom door as this room was rarely used. These sensors recorded the state (open or closed) every 5 minutes (state monitoring) as opposed to the event monitoring sensors used at UTH and CS2. The front door was monitored with an EasyLog EL-USB-5 logger which used a magnet to record the open/closed state of the door, this sensor recorded every time the door was opened or closed (event monitoring). Figure 3.3 shows a floor plan of the dwelling and locations of sensors. Since OAF was not used for ventilation rate analysis, further measurements such as external CO_2 and air permeability were not taken.

The occupants were asked to record when the last person left the dwelling (occupancy ends) and when the first person entered the dwelling (occupancy begins). There were 62 reported start or end of occupancy times.

3.6.3 Flats for investigation of ventilation in occupied homes

These case study dwellings formed a significant part of the research and are therefore discussed in detail. These homes were monitored from summer to winter so that the variability in ventilation could be explored, and interviews with the participants were used to investigate the participants' ventilation-related practices, how the planned ventilation system featured in their practices and other ways the participants influenced ventilation and the need for ventilation at home.

A housing developer agreed to support this research by helping to identify a completed development suitable for the project, and initiating discussion with the property management team. The initial requirements were: to have been built to the 2010 revision of ADF and to be naturally ventilated with intermittent extract (system 1 in 2010 ADF). A development (CS1) was selected, showing a natural ventilation system on planning drawings. Recruitment of four dwellings went ahead from February 2019 and equipment was installed in April 2019. Upon installing the equipment it was found that the dwellings in CS1 in fact have an MVHR ventilation system (system 4 in 2010 ADF). Further study of these properties was not in line with the aims of this research, given the emphasis on the use of trickle vents, which are not present with MVHR. Equipment was removed from the CS1 flats later in April 2019. Three of the participants at CS1 agreed to take part in the practice interviews which took place in August 2019. A second development was identified, CS2, this development is ventilated with continuous mechanical extract ventilation and trickle vents (system 3 in ADF). Whilst not naturally ventilated, the system 3 ventilation strategy is increasingly common in England (MHCLG, 2019b) and includes the use of trickle ventilators, therefore this was selected as an interesting and appropriate case study for this research.

The next section describes the recruitment of the participants (the same strategy was used at CS1 and CS2). Information about CS2 development, the participants and their flats follows. Finally the data collected at CS2 is described.

3.6.3.1 Recruitment

Flyers were posted in all letterboxes at CS1 and CS2, which described the research in broad terms and outlined the requirements for any participants of the study. A £25 voucher was offered as an expression of thanks to those who took part. The author's contact details were given for potential participants to state their interest. There were between 150 and 200 flats at both CS1 and CS2, and of these five interested households responded at both developments. When potential participants contacted the author they were given the full participant information sheet and consent form that would need to be signed to take part in the research, and they were also encouraged to ask any questions and seek any clarifications about the research. At both developments, four households subsequently agreed to take part in the research. This means that the sample is self-selected, this was necessary in order to gain access to the participants' homes.

3.6.3.2 Description of the development and case study dwellings

CS2 is a housing development in London which was converted from an office built in the early 1980's to a block of flats in 2015. The building has an L-shaped footprint, is 8 storeys high and contains over 100 flats. Most flats have one exposed facade, but those on the corners have two. The long edge of the building is parallel but set back from an A-road, while the opposite side faces trees, a stream and a railway line. The building has a distinctive post-modern form and therefore pictures of the building and the flats have not been included to preserve the anonymity of the participants.

The one-bedroom flats (A and D) had halls connecting to open plan kitchen-living rooms, a bedroom and a bathroom. The studios (B and C) combined kitchen, living room and bedroom in the same room, with a separate bathroom. The flats had a utility cupboard containing a washing machine, heat interface unit for the communal heating system and an isolation switch for the centralised ventilation system. All the flats had electric ovens and 4-ring electric hobs with a recirculating cooker hood. Figure 3.5 gives an indication of the floor plan in the studio and 1-bed flats, although these do not exactly reproduce any of the studied dwellings in order to preserve the anonymity of the participants. Table 3.4 gives the floor areas of the flats.

Since the conversion from offices to residential housing in 2015 constituted a change of use, the dwellings were required to meet the ADF standards for ventilation in new dwellings. The planned ventilation strategy at CS2 was continuous mechanical extract ventilation system, system 3 in ADF 2010. The extract system was centralised with the extract points in the kitchen, bathroom and utility ducted to a central fan and then ducted to outdoors. The housing developer shared the ventilation drawings showing the locations of the ducts and fans, it is notable that these show that the extract outlet is above one of the window lintels in each flat. All windows had trickle vents installed at the top, meaning that the MEV outlet was very close to the location of one of the trickle vents in each of the flats. This is a concern as it provides a possible short-circuit pathway in which air removed from the flat via the ventilation system is subsequently drawn back into the dwellings via the trickle vents. The ventilation system commissioning documents were shared by the developer, these show that for the majority of flats in the development (especially above the ground floor) the commissioning professional noted that the ventilation duct was not properly connected to the exterior wall. This raises another potential route for short-circuiting as the air drawn through the MEV system may leak back into the dwelling at the location of the imperfect connection to the wall. The locations of the ducts and outlets were not verified on site due to the difficulty of accessing the space above the ceiling in which the ducts were located.

The flats had windows that could be tipped (hinging from the bottom of the window up to a maximum opening of about 10 cm at the top) or tilted inwards (unrestricted hinge on the side of the window). Figure 3.4 shows a schematic of these type of windows. The studio flats had two windows: one in the bedroom area and one in the living room area. Flat A had one window in the bedroom and two in the living room, one of which was a double casement window. Flat D was on the corner of the building and had one window in the bedroom and 4 in the living room, of which three were double casement windows. Appendix B of ADF gives details of the size of windows required for adequate purge ventilation. This states that if the opening angle is less than 15° then the window is not appropriate for purge ventilation. The windows at CS2 would need to be tilted to meet ADF's standard for purge ventilation, one of the occupants in Flat B noted that his windows could not tilt open and therefore purge ventilation was not available in Flat B.

The names of the participants have been changed to preserve anonymity, the first letter of the pseudonyms is the same as the letter used to identify the flat where

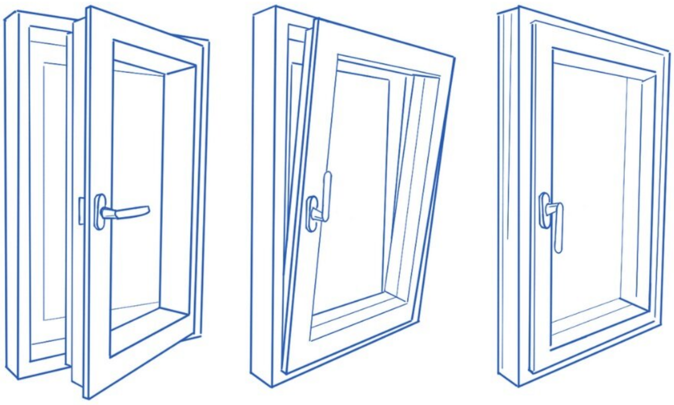


Figure 3.4: Schematic of the tip and tilt windows at CS2, from left to right the window positions are tilted, tipped and closed. Figure from Bauwerksolutions.com (2019).

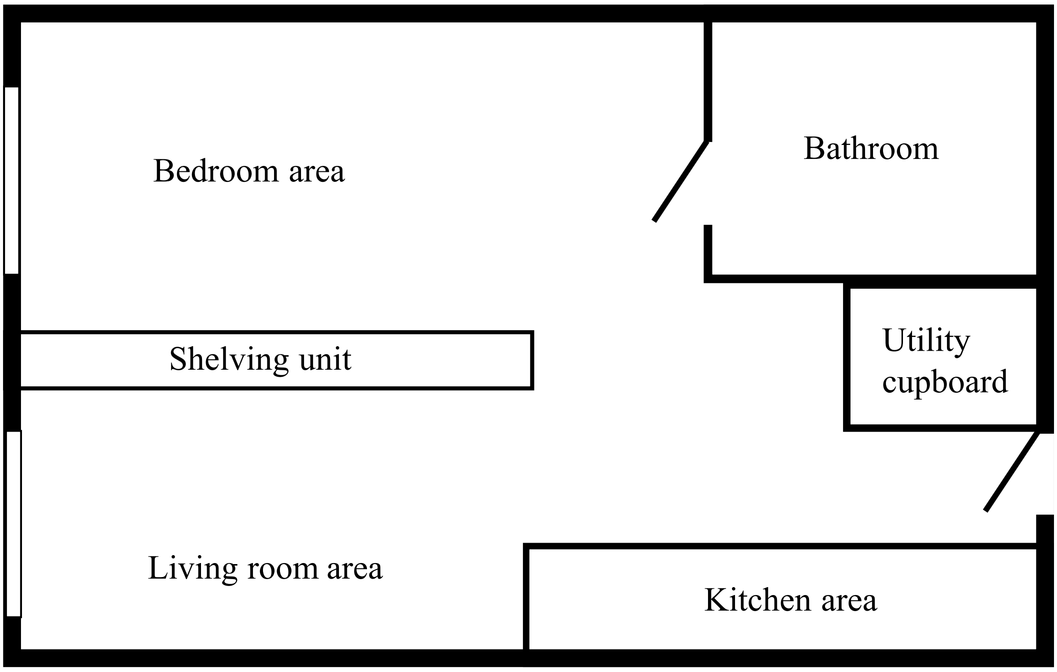
Table 3.4: Details of the four flats and participants at CS2.

Flat	Participants	Dwelling Type	Floor	Floor Area (m^2)
A	Aaron and Alice	1-Bedroom	1st	49
B	Brandon or Bridget	Studio	Ground	33
C	Cal	Studio	Ground	33
D	Darren	1-Bedroom	Ground	42

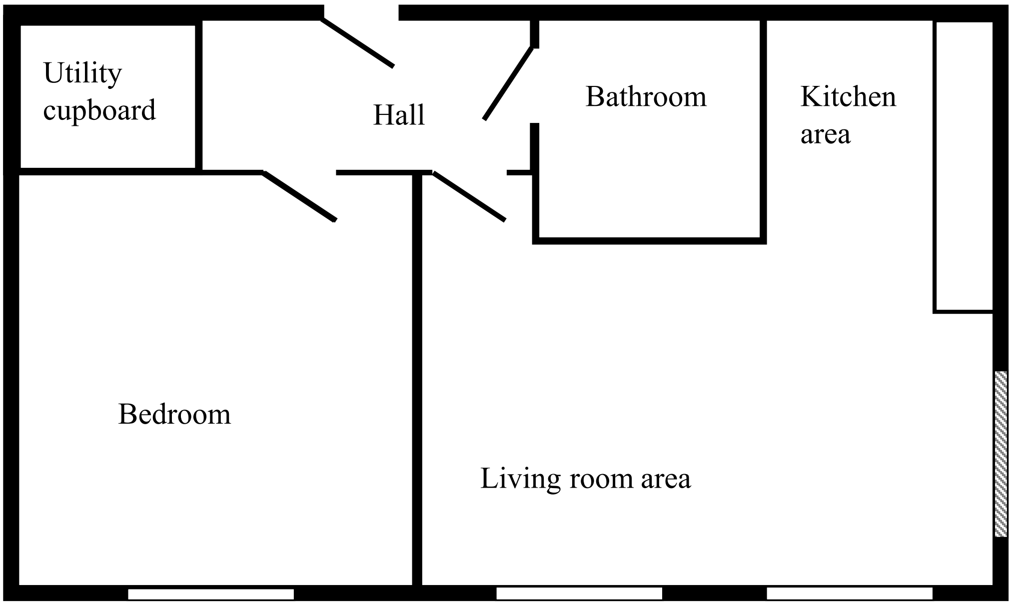
they lived, see Table 3.4. Brandon and Bridget did not live in the flat at the same time, Brandon owned the flat and lived there from the beginning of the monitoring campaign in June 2019 until he rented it to Bridget between October 2019 and the end of the monitoring campaign in January 2020. Bridget and Darren were privately renting and all other participants owned their flats. Alice frequently worked from home, Brandon worked from home occasionally, Bridget was a University student and all other participants worked full time in offices.

3.6.3.3 Description of equipment used and data collected

This section is split into sections describing the continuously monitored data, the one-off measurements and the interviews.



(a) Studio flat with floor area 33 m^2. One external wall with windows as indicated.



(b) One bedroom flat with floor area of approximately 45 m^2. Flat A had one external wall, as indicated by the solid windows, Flat D had an additional external wall indicated by the hashed window.

Figure 3.5: Approximate layouts of the studio and one bedroom flats at CS2. For the studio flats,

3.6.3.3.1 Monitored data. The flats at CS2 were monitored between June 2019 and January 2020. Eltek GD47 sensors, with measurement ranges and stated accuracies as in Table 3.2, monitored temperature, humidity and CO_2 every five minutes. These sensors were placed in the bedroom, living room and hall of Flat A, the bedroom and living room of Flat D and in the bedroom section of the studio flats. Eltek AQ110 sensors were placed in all kitchens, these monitored temperature, relative humidity, CO_2, CO, NO_2, VOCs and PMs of three sizes (0-1μm, 1-2.5μm, 2.5-10μm) every five minutes. The additional air quality data from the AQ110s were used to assess whether conditions were in line with WHO indoor air quality guidance for the measured compounds, and in case the participants raised IAQ concerns for which supplementary data would be useful. The CO_2, temperature and humidity sensors inside AQ110s were the same a the Eltek GD47s so the stated accuracies and measurement ranges were the same.

All indoor sensors were placed so as to be out of the participants way, away from heat sources, out of direct sunlight and away from doors and windows. Wherever possible they were installed on tables, shelves or kitchen counters. All indoor sensors were placed between 1m and 1.5m above floor level. The sensors were mains operated so the availability of sockets sometimes influenced placement. The occupants were always asked to check that the locations of the sensors were acceptable, and then were asked not to move the sensors for the duration of the research.

HOBO UX90-001M state loggers with magnetic relays were installed on all doors except the door to the utility cupboard in all flats. All window openings were monitored with the same sensor, except in Flat D. There were four windows in the kitchen-living room of Flat D, three of these were double casement windows, giving seven openings in total. These double windows were only monitored on one side due to the large amount of equipment required to monitor all of them, and because Darren stated that the kitchen window, with one opening, was most used and the rest were almost never used. All proximity sensors were event logging (recorded the time stamp each time the magnetic switch opened or closed). The same kind of sensors were used at CS2 as at UTH and a similar issue with the

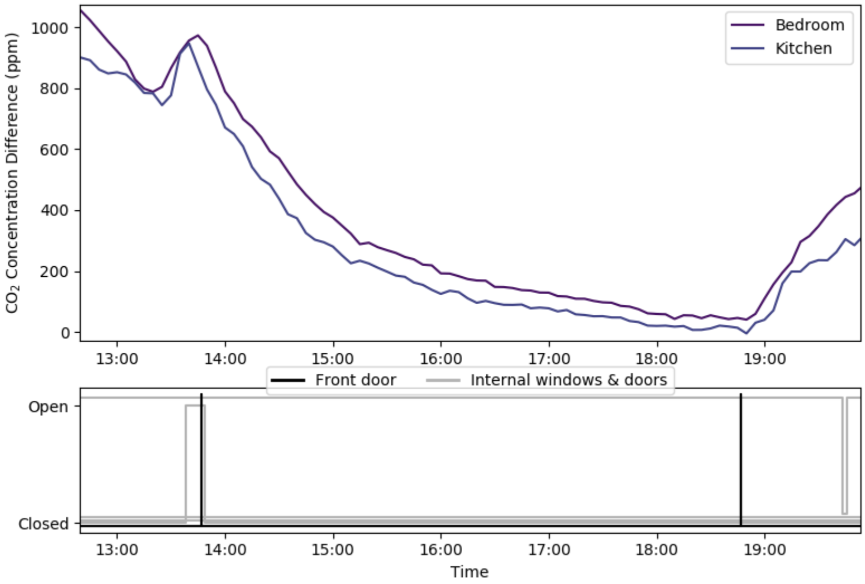


Figure 3.6: Example of the uncorrected proximity data showing a period where the internal clock drifting is apparent. The CO_2 concentration falls consistently between the front door use shortly before 14:00 and shortly before 19:00, there is only one recorded use of a window during this period, less than one minute after the front door first closes, this means the dwelling was likely unoccupied during this period and the window sensor's internal clock had drifted relative to the front door sensor. The time data from the window across the whole monitoring period was reduced by a linearly increasing offset such that the corrected data did not indicate closure during the time between front door use shown in this figure.

internal clocks drifting was observed as described in Section 3.6.1.2. At CS2, no manual records of occupied and unoccupied times were kept, Figure 3.6 illustrates how this data was corrected using periods in which there was at least several hours between front door use. During these periods, if there was no CO_2 rise nor change in state of doors or windows in the middle of the period, but one of the internal doors or windows changed position a few seconds or minutes after the front door closed or before the front door opened, then this was interpreted as indicating a discrepancy in the internal clocks. A linearly increasing offset was applied to the time data of the indicated sensor such that it no longer changed position in between the front door closing and opening during the period inspected. The maximum offset applied across all sensors installed at CS2 was 380 seconds. This correction was important for the OSA discussed in Section 4.1, but otherwise did not affects the results.

An Eltek GD47 was placed in a weather-proof box and installed outside CS2 to monitor external CO_2, temperature and humidity in July 2019. The power supply was fed through a window in reception such that the window could still be closed in winter. The sensor was approximately 2 meters away from the building, close to ground level at the foot of a walled flower bed which separated a parking area and the building. The sensor was shielded from direct sunlight in this position. The power supply was located in the reception of CS2, unfortunately this was switched off twice causing two periods of missing external data; for three weeks in August 2019 and six days in October 2019.

Offsets in measured CO_2 concentrations between different sensors were accounted for throughout the monitoring period. Shortly after the external sensor was installed, once in the middle of the campaign and at the end of the monitoring campaign all Eltek GD47s and AQ110s were collected and placed next to each other for a period of two to seven days, recording data every five minutes. During these periods the mean offset between each sensor and the sensor usually placed outdoors was calculated. This offset was removed in the calculation of the CO_2 concentration difference used to calculate the ventilation rate. If there was any change in the offset between the co-location measurement periods, then the offset value used in calculating the CO_2 difference was linearly interpolated between the two co-location periods, this is discussed further in Section 4.2.1. While this is not as rigorous as calibrating the instruments, the absolute CO_2 concentration was not the focus of this work and Etheridge (2012) states that precise calibration is not required for the tracer gas decay technique, as long as the zero is stable. The above procedure verified the zero concentration difference between the indoor and outdoor sensors throughout the monitoring period.

The proximity sensors were collected at the same time as the Eltek sensors for the co-location measurements. This meant their battery and memory level could be checked.

3.6.3.3.2 One-off measurements. Air permeability measurements were taken at Flats B, C and D in January 2020. No measurement was taken in Flat A because the

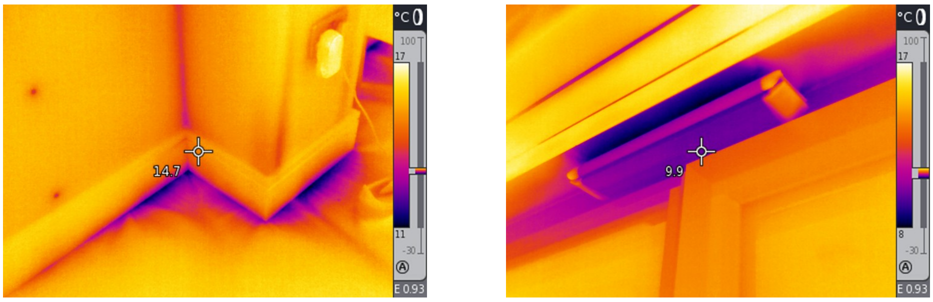
Table 3.5: Air permeability and trickle vent measurements.

Flat	Air permeability at 50Pa ($m^3m^{-2}h^{-1}$)	Inferred trickle vent ELA (mm^2)	Labelled trickle vent EA (mm^2)	Trickle vent EA required by ADF (mm^2)
A	-	-	15000	5000
B	4.5	900	10000	2500
C	5.9	1700	10000	2500
D	5.7	-	25000	5000

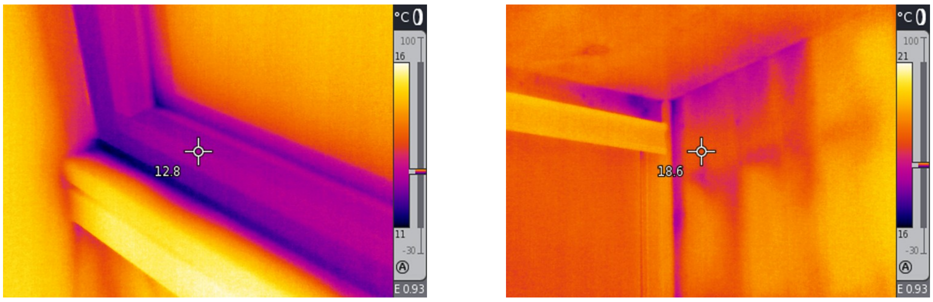
participants were unavailable on the date which suited the other three participants. Air permeability measurements were carried out accordance with ATTMA (2016) guidance with a Retrotec 6000. Measurements were taken in depressurisation only in all cases, values are reported in Table 3.5.

An additional set of pressure and flow rate measurements were taken in Flats B and C with the trickle vents open to approximate the additional equivalent leakage area (ELA) of open trickle vents. Table 3.5 presents the results from these pressurisation tests. According to BS EN 13141-1 (2004) trickle vent effective area should be measured at a pressure difference of 1 Pa. It should be noted that the inferred ELA of the trickle vents presented in Table 3.5 was calculated using values fitted at 50 Pa due to the inaccuracies associated with extrapolating pressurisation test results down to 1 Pa, the results give an indication of the area of the trickle vents but are not equivalent to the ELA.

Air leakage paths were qualitatively investigated in Flat D. A thermal camera was used to show areas that were particularly cold due to outdoor air being drawn in while the dwelling was depressurised. There were clear flow paths around the wall-floor join, through the closed trickle vents and around the bedroom window as shown in Figures 3.7 a, b and c respectively. It also appears that air was penetrating into the partition wall between the bedroom and kitchen, as shown in Figure 3.7 d. When Figure 3.7 d was discussed with the developer, they indicated that when the building had been converted from flats into offices the airtightness of the original envelope would not have been investigated or improved. Since the flats were dry-lined any imperfection in the original envelope could easily cause local leakage



(**a**) Floor line (**b**) Closed trickle vent



(**c**) Window frame (**d**) Ceiling line of a partition wall

Figure 3.7: Thermal images taken in Flat D while depressurised during the winter, the dark colours indicate cooler temperatures and are indicative of the locations of air leakage paths in these locations.

paths.

The depth of all door undercuts were measured. An undercut of 10mm is required for all internal doors according to ADF. Front doors should not have undercuts. Table 3.6 gives the depths of the undercuts for each door, 5 of 8 internal doors had undercuts smaller than required. None of the flats had installed new floor coverings which could have affected the depth of undercut.

Extract fan flow measurements were taken after interviews so that discussion of these results did not influence the interview. Flow measurements were taken using an Observator DIFF powered flow hood wherever possible, this is the unconditional method used for commissioning ventilation systems, described in BSRIA (2015). This device automatically corrects for back pressure (the reduction in flow through the fan due to the resistance caused by the presence of the flow hood). In Flats A and B due to the space in the utility cupboard it was not possible to use the Observator DIFF and instead a Testo 417 vane anemometer with a round funnel was used. This does not correct for back-pressure, so the results will be lower than the flow rate

Table 3.6: Depths of undercut for each door in each of the case study dwellings at CS2

	Door Undercut Depth (mm)			
Flat	**Front**	**Bathroom**	**Bedroom**	**Living room**
A	5	9	6	4
B	3	14	N/A	N/A
C	10	10	N/A	N/A
D	11	5	5	10

Table 3.7: Flow rates required by ADF and measured in the CS2 flats. Values in brackets are standard deviations of the three measured values.

	Kitchen (l/s)	Bathroom (l/s)	Utility (l/s)	Whole Flat (l/s)
ADF whole flat	-	-	-	13
ADF minimum high rate	13	8	8	-
Flat A	13.1 (0.1)	5.8 (0.3)	12.5 (0.1)	31.4 (0.3)
Flat B	11.2 (0.2)	6.75 (0.5)	7.1 (0.0)	25 (0.5)
Flat C: before cleaning	13.2 (0.0)	4.0 (0.2)	7.4 (0.1)	24.6 (0.3)
Flat C: after cleaning	-	8.2 (0.1)	-	28.8 (0.1)
Flat D	6.1 (0.1)	2.9 (0.2)	9.8 (0.4)	18.9 (0.4)

in normal operation. The flow rate through each inlet was measured three times. Table 3.7 gives the mean flow rates and standard deviations, along with the required extract flow rates given in ADF (HMG, 2013b).

According to the ventilation drawings from the developer the boost function would be triggered by an increase in humidity. This does not follow the design in ADF since boost activation by humidity is not appropriate in sanitary accommodation since odour is the main pollutant. Attempts were made to activate the boost function of the extract systems by both increasing the humidity and by use of the bathroom light; no increase in flow rate was measured.

There was one instance in which the flow rate was measured before and after cleaning of the extract inlet. In Flat C, Cal had noticed that the area between the concentric circles of the extract fan terminal in the bathroom was visibly dusty. When the author measured the flow rate through this terminal using a step ladder to reach, Cal asked to use the step ladder to clear out the dust. The flow rate was then re-measured and this result is also given in Table 3.7.

3.6.3.3.3 Interviews. Participant interviews were conducted at the same time as the equipment was removed from the dwellings. This was so that the questions and topics covered in the interview did not influence the behaviour of the occupants during the monitoring period.

Interviews took place in the participants' homes, except the interview with Brandon which took place by telephone because Bridget was living in Flat B at the time of the interview. Interviews ranged in length between 40 minutes and 1 hour. It should also be noted that Bridget was not a native English speaker and at times our communication during the interview was hindered.

3.7 Summary

Chapter 2 concluded with three research questions and the present chapter has detailed the approach taken to answer these questions. This work has adopted a multiple case study research design with mixed methods. The exploratory nature of the ventilation measurement method development, the extended monitoring campaign required and the need to integrate physical and social perspectives are all well suited to a detailed investigation of a small number of cases. This approach was designed to investigate the complex and interacting factors affecting ventilation in homes. In particular, the combination of technical and social research was adopted to explore the participants' practices related to ventilation, their impact on ventilation, and their experiences of the conditions in the home.

The methods adopted to answer each of the research questions were presented in this chapter, the rest of the thesis presents the results, analysis and conclusions of the research. Chapter 4 discusses the method development including the development and testing of the occupancy algorithm, analysis of the effect of changes in the outdoor CO_2 concentration, the development and testing of the analysis algorithm for identifying and analysing periods of data for ventilation rate analysis and finally a discussion and quantification of the uncertainties associated with the measurements. Chapter 5 gives the findings relating to the adequacy of ventilation in homes, both in terms of the experiments relating to specific actions at UTH, and the six month monitoring campaign at CS2. Chapter 6 presents the findings relating to the ventilation practices of the participants at CS2. Chapter 7 provides a global discussion, drawing the findings across all streams of the work together and gives the overall conclusions of the work.

Chapter 4

Method Development and Implementation

Through the literature review in Chapter 2 it was argued that current methods for measuring ventilation cannot easily be used to assess the variation of ventilation in occupied homes. One of the key requirements of the method used for this research was that extended periods of data could be analysed to facilitate long-term measurement campaigns, reducing reliance on one-off ‘snap-shot’ measurements. The previous chapter introduced the core techniques for the ventilation measurement method used in this research.

This chapter presents the results of work to develop a ventilation measurement method which can be applied in occupied dwellings to measure temporally disaggregated ventilation rates and the uncertainties associated with the developed method. The ventilation measurement method is based on the CO_2 decay technique, as discussed in Section 3.2. This chapter is split into four sections. The first two sections, 4.1 and 4.2, describe the development, implementation and limitations of the occupancy status algorithm (OSA) and automatic analysis algorithm respectively. Section 4.3 discusses uncertainties of the ventilation rates measured for this research. And finally Section 4.4 summarises and concludes the chapter.

4.1 Development of the occupancy status algorithm

As discussed in Section 3.2.3, the ventilation literature has relatively few examples of methods for determining when a space is occupied. Where occupancy has been recorded this has tended to be through occupant diaries, or by hand-picking sections of data for analysis. This was not appropriate for this research because the monitoring period took place over several months and determining occupancy by-hand or asking occupants to record their movements over this period would have been unnecessarily time-consuming. Previous methods in the wider occupancy literature have made use of CO_2 data and combining this with other streams of data has been shown to be able to overcome some of the problems of using CO_2 alone (Chen et al., 2018). In the present case, door and window opening data were to be collected to aid interpretation of the conditions in the dwelling this presented an opportunity to combine CO_2 and door and window opening data to design the occupancy algorithm. This section presents the principles and testing of the occupancy status algorithm (OSA) developed for this research.

4.1.1 Principles of the OSA

The algorithm developed in this research has similar principles to the Dedesko et al. (2015) method. The algorithm is based on the logic that if any of the internal doors or windows change state between the front door closing and the next time it opens, then the dwelling must be occupied during that period. If none of the doors or windows change position, then the CO_2 concentration gradient is tested on the basis that if the CO_2 rises significantly then the dwelling is highly likely to be occupied (or another significant source of CO_2 is present, which precludes use of the decay method). The first 30 minutes of CO_2 data after the front door closes are disregarded if the period under investigation is sufficiently long, this ensures that if the door to a room with a high concentration of CO_2 is opened shortly before the dwelling becomes unoccupied and causes the concentration of CO_2 to rise in adjacent rooms, this period is not falsely identified as occupied. Periods where the dwelling is unoccupied for less than 30 minutes could falsely be identified as occupied for this reason, meaning that some valid CO_2 decays could be missed by

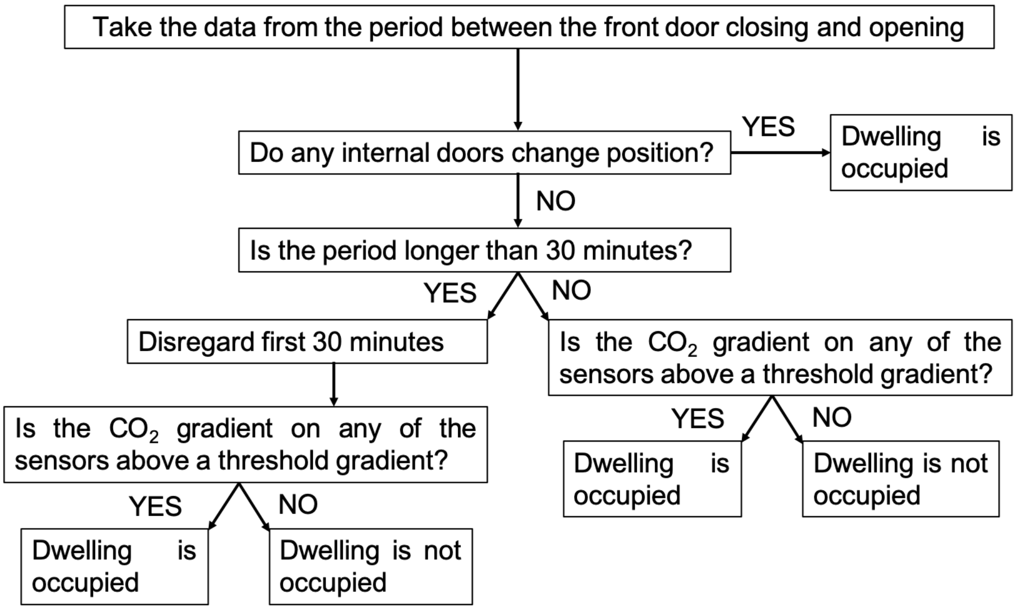


Figure 4.1: Flow chart of the decision making of the occupancy status algorithm.

the algorithm. However, with data collected every 5 minutes, it is unlikely that the CO_2 concentration would both rise steeply enough to be identified as occupied and decay for long enough to give a sufficient number of points to fit an exponential decay, so this is unlikely to significantly affect the results. The flow chart in Figure 4.1 shows the decision making process used by the algorithm. The algorithm was written in the Python programming language.

4.1.2 Testing and developing the OSA

A case study monitoring campaign was set-up in an occupied flat, OAF, to provide data for testing the occupancy detection algorithm, the characteristics of the dwelling and monitoring campaign were described in Section 3.6.2.

Calculation of the CO_2 gradient required consideration of how to smooth the CO_2 data, since it showed fluctuations due to noise, and an appropriate threshold gradient for indicating the presence of occupants. The gradient was calculated as follows:

$$Gradient_i = \frac{\Delta\overline{CO_{2,i}(t)}}{\Delta t}, \tag{4.1}$$

where $\overline{CO_{2,i}(t)}$ is the mean of the CO_2 concentration readings for sensor i over the preceding 15 minutes, this reduced the effect of fluctuations due to noise without significantly attenuating the signal. Additionally, only CO_2 data between front door closure and the next front door opening was used in this calculation so that occupied conditions did not affect the calculation of the gradient. The threshold value for the gradient was empirically determined in the absence of a clear theoretical case. The threshold value which gave the best agreement with occupant records of occupancy at OAF was 100 ppm per hour, with lower gradients increases in CO_2 in the noise were sometimes caused the dwelling to be classified as occupied, while greater values did not improve agreements with the occupants and could result in occupied data being misclassified as unoccupied.

The OSA was in agreement with the occupant records in 87% of cases, Figure 4.2 shows the CO_2 and door and window data for a case that the OSA agrees with the occupant records. Agreement between the algorithm and occupant records was calculated as follows: when the period before an occupant reported a start of occupancy was classified by the algorithm as unoccupied this counted as one instance of the algorithm correctly classifying the occupancy. Similarly, when the period after the occupant reported start of occupancy was classified by the algorithm as occupied this counted as one instance of the algorithm correctly classifying the occupancy (and vice versa for end of occupancy data). The percentage of agreement was then calculated.

Disagreements between the occupant records and algorithm were investigated through detailed study of all the measured parameters to see if changes could be made to improve performance in later deployments of the method. In some cases it was likely that the disagreement was due to window opening - the temperature was seen to rapidly drop but the CO_2 did not rise. In other cases the front door was in frequent use (likely because the occupants were arriving or leaving for work at similar times), in 10 of the 16 cases of disagreement the front door was opened with a frequency of more than 30 minutes. The internal door state was recorded every five minutes at OAF, rather than every time the door state changed. This meant that if internal doors were opened and closed within a five minute period then this was not reflected in the recorded data and the algorithm was unable to identify these

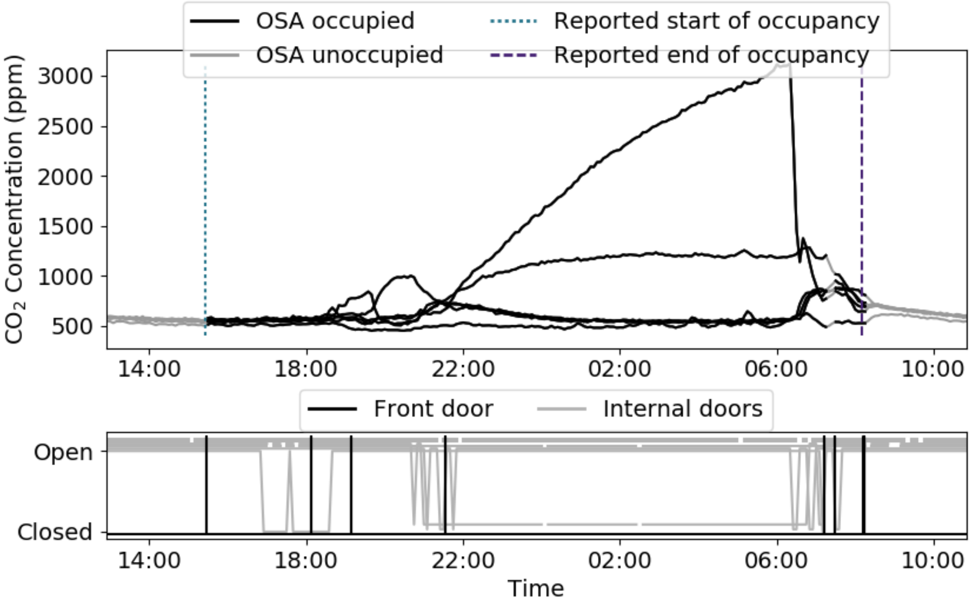


Figure 4.2: Example of when the dwelling was occupied and unoccupied as determined by the occupancy status algorithm (OSA), and the occupant reports of start and end times of occupancy. The top part of the graph shows the measured CO_2 concentrations in each of the rooms. The bottom part of the graph shows the open or closed status of the doors.

periods as occupied, see Figure 4.3 for an example of the data where frequent front door use was thought to prevent the OSA from correctly identifying an occupied period. It should be noted that neither of the failures of the OSA shown in Figure 4.3 would result in the analysis of CO_2 decays during occupied periods, in the first case because the CO_2 remains close to outdoor concentrations, and in the second because the incorrectly identified period is 20 minutes in duration which is less than the minimum decay period (discussed in Section 4.2.3.3).

4.1.3 Subsequent deployments of the OSA

Several improvements were made to facilitate improved accuracy in the subsequent deployment of the method at CS2. Window sensors were included and all proximity sensors were event logging rather than state logging. This is expected to resolve the issues caused by a lack of CO_2 increase due to window opening and caused by frequent use of the front door. Inferred window opening and frequent door use were associated with the majority of incorrectly classified cases by the OSA at OAF. It is

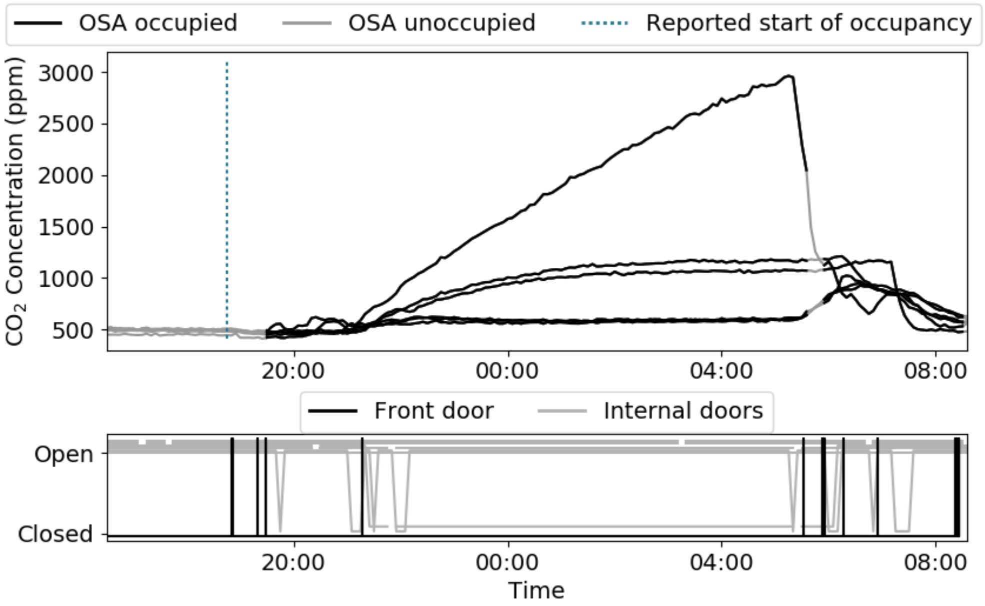


Figure 4.3: Example of when the dwelling was occupied and unoccupied as determined by the OSA, and the occupant reported start of occupancy. The top part of the graph shows the measured CO_2 concentrations in each of the rooms. The bottom part of the graph shows the open or closed status of the doors. The frequent use of the front door at approximately 7 pm and 6 am prevents the algorithm from identifying these periods as occupied.

expected that if they had been present the agreement between the OSA and occupant reports would likely have been at or above 95%.

Subsequent deployments of the method at CS2 used the same smoothing for calculation of the gradient and the same gradient threshold, although at CS2 ΔCO_2 was used instead of the indoor CO_2 data. This means that the algorithm is less sensitive to fluctuations in outdoor CO_2 causing indoor CO_2 rises (see Section 4.2.1).

4.1.4 Limitations of the OSA

This algorithm is reliant on accurate door and window opening data. As discussed in Sections 3.6.1 and 3.6.3, the internal clocks in the proximity sensors drifted relative to each other. This was first observed at UTH and subsequently at CS2. The time drifts were corrected manually as described in the previous chapter, since there was no clear way to automate or objectively correct the data retrospectively. This manual correction could lead to small errors in the time data, however, this error would be on the order of seconds and so is unlikely to significantly affect the analysis. Future uses of the method would ideally use equipment which is less prone to time drift.

Additionally, interpreting CO_2 rises as indicating occupancy could sometimes incorrectly identify the status of the dwelling. If there were significant flow paths with adjacent dwellings then the presence of occupants in these adjacent properties could cause a rise in CO_2 large enough to cause the OSA to classify the studied dwelling as being occupied. However, such data would be inappropriate for ventilation analysis because, despite the occupancy status of the studied dwelling, a significant source of CO_2 would be represented by the flow of air from the adjacent dwelling.

It is also possible that windows or doors left open could close due to wind during unoccupied periods. Only one period was identified in which this appeared to have happened so although it is possible that further occurrences were not identified it is thought to happen with very low frequency.

The data classified as unoccupied by the OSA was passed to an analysis algorithm which identified and analysed periods of data appropriate for decay analysis, the following section discusses the development of this algorithm.

4.2 Automatic analysis programme

As this project has set out to collect data spanning several months, it was necessary to write an algorithm which could identify periods of decaying CO_2 suitable for decay analysis and fit these identified decays to the expected exponential model. The structure of this analysis code is outlined here:

1. Raw CO_2 data converted to ΔCO_2 (indoor-outdoor concentration difference).

2. Data separated into occupied and unoccupied data.

3. Exclude unoccupied periods where the CO_2 is shown to be spatially inhomogeneous.

4. Periods of unoccupied and spatially homogeneous data are analysed to identify periods of decaying ΔCO_2 suitable for analysis.

5. These periods of decaying ΔCO_2 are fitted to the ventilation model to calculate the ventilation rate.

Each of these stages is discussed in turn in the following subsections, both in terms of how these issues were handled in the analysis algorithm and in terms of their effect on the measured ventilation rates.

Following this, Section 4.3 discusses the uncertainties associated with ventilation measurement using the method presented herein. Aspects of this uncertainty are referred to in the present section and this highlights where there is further elaboration of these issues in the following sections. The present section describes how the data were analysed and why particular decisions relating to the automatic analysis algorithm were taken.

4.2.1 Outdoor CO_2 concentration calculation

Initial results from UTH highlighted the potential significant impact of the variability of the outdoor CO_2, this section presents the way ΔCO_2 was calculated for the UTH data with and without the external sensor. Subsequent measurements of external CO_2 and calculations of ΔCO_2 at CS2 are discussed.

4.2.1.1 Calculation of ΔCO_2 at UTH

Figure 4.4 shows the CO_2 data collected during the early part of the research at UTH in which external CO_2 was not monitored. Guo and Lewis (2007) used an unoccupied period to estimate the outdoor CO_2 concentration. For this research the mean CO_2 concentration during a three-day period in which UTH was unoccupied was taken as the external CO_2 concentration. This period is highlighted in Figure 4.4. This period began 24 hours after UTH became unoccupied, to allow the indoor concentration to return to outdoor concentration.

Figure 4.4 also highlights the CO_2 concentrations recorded during a five day period in which the test house was unoccupied; the CO_2 rises and falls by over 100 ppm during this time. Excess atmospheric CO_2 in urban locations has been referred to as a CO_2 dome (Mitchell et al., 2018). In early work on the CO_2 dome in the city of Phoenix, Arizona, Idso et al. (2002) found urban CO_2 up to 200 ppm above the

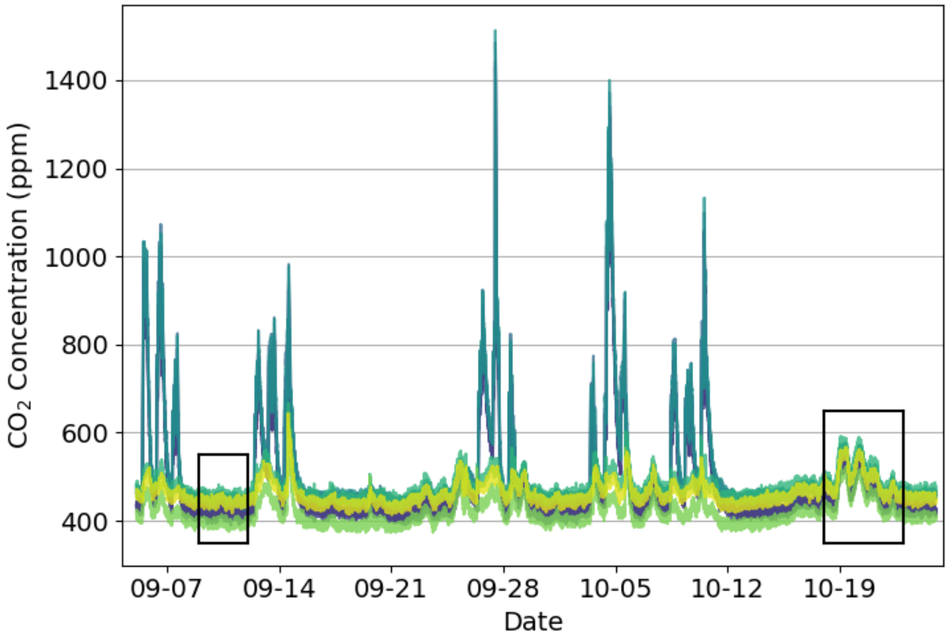


Figure 4.4: Graph of CO_2 concentration in the test house over the first two months of monitoring, offsets between the sensors can be seen. The first box shows the 3 day period used to estimate the background CO_2 concentration for each sensor. The second box shows clear variability in the CO_2 concentrations during a 5 day period in which the test house was never occupied.

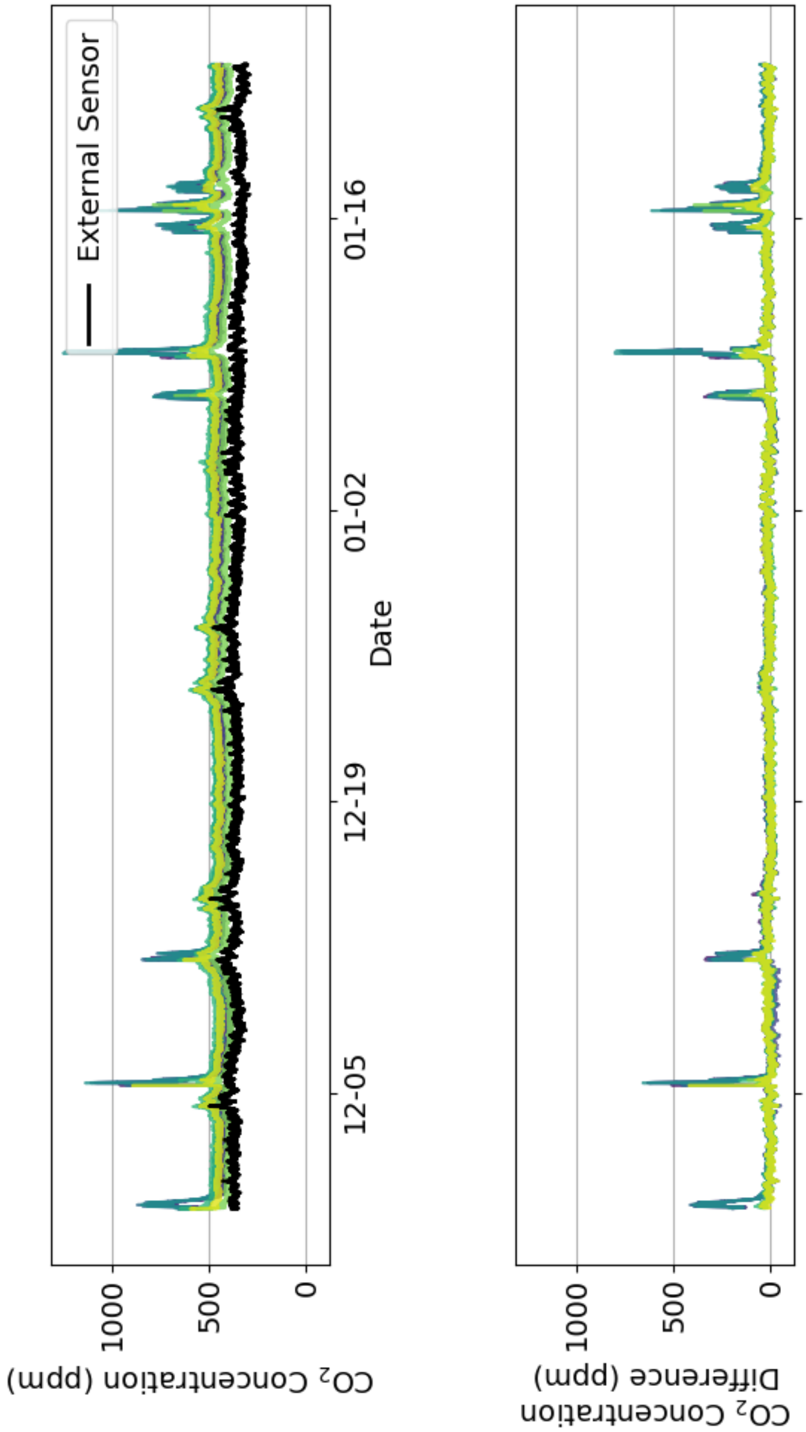
urban minimum and 220 ppm above the rural background. Urban CO_2 domes are related to anthropogenic CO_2 emissions and significant sources include combustion of natural gas for heating, vehicular emissions as well as industrial processes such as cement production (Mitchell et al., 2018). The amount of excess CO_2 in the urban CO_2 dome varies diurnally and seasonally. Diurnal variations are associated with temperature changes; surface temperatures drop at night causing a temperature inversion in which air at lower altitudes is cooler than air at higher altitudes, this causes the lower level of air to become trapped. When this happens, CO_2 emissions released near the surface do not mix well with the layers of air above and urban CO_2 concentrations increase. Following this, heating of the ground by solar irradiance during the day increases mixing between atmospheric layers of air and this dilutes urban CO_2 concentrations (Idso et al., 2002). Photosynthesis further reduces CO_2 during the day. Larger excess CO_2 concentrations are observed in the winter due to increased combustion for heating, more frequent and persistent pools of cold air which trap emissions near the surface and reduced photosynthesis (Mitchell et al., 2018).

The excess CO_2 shown in Figure 4.4 may be related to a temperature inversion since a serendipitous simultaneous measurement of outdoor CO_2 in London exhibited similar concentration changes over the same period (J. Wingfield, personal communication). UTH is located on a busy main road and CO_2 from vehicle emissions could be a strong local source. The data collected at UTH and the literature relating to urban CO_2 domes indicates that continuous measurement of the outdoor CO_2 will improve the accuracy of the ventilation measurement methods discussed here. This is because any CO_2 based ventilation measurements taking place during such an event would be biased by the use of an assumed constant outdoor CO_2 concentration. An analysis of the effect of assuming a constant external CO_2 concentration on the calculated ventilation rate is presented in Section 4.2.3.

An outdoor sensor was installed at the end of November 2018, as described in Section 3.6.1, to mitigate against such variations in external CO_2 concentration. This sensor exhibited a significant long-term drift towards lower CO_2 concentrations and a systematic offset to the concentrations recorded by the Eltek CO_2 sensors, see Figure 4.5a. The offsets between the indoor and outdoor sensors were estimated at the beginning and end of the monitoring period and linearly interpolated between these times to estimate the offset during the monitoring period. The mean offset was 73 ppm at the start of the monitoring period and 113 ppm at the end. The concentration difference was then calculated as:

$$\Delta CO_{2,i}(t) = CO_{2,i}(t) - CO_{2,outdoor}(t) - k_i(t), \tag{4.2}$$

where $\Delta CO_{2,i}(t)$ is the CO_2 concentration difference between sensor i and outdoors, $CO_{2,i}(t)$ is the CO_2 concentration measured by sensor i. $CO_{2,outdoor}(t)$ is the mean CO_2 concentration measured in the hour preceding time t, this was to minimise the impact of noise and other short term variations, whilst ensuring that the calculated concentration difference at any point in time is not inappropriately associated with



(a) Raw CO_2 concentration from the external sensor and all internal sensors.

(b) Calculated CO_2 difference for each internal sensor.

Figure 4.5: Raw CO_2 concentration and calculated ΔCO_2 concentration at UTH.

future outdoor concentrations. $k_i(t)$ is the estimated offset between indoor sensor i and the outdoor sensor at time t. Figure 4.5b shows the resulting concentration differences over the measurement period. The concentration difference remains close to zero except when there are concentration increases associated with the ventilation experiments, suggesting that the calculated offset is a reasonable approximation. The limitations associated with this calculation of ΔCO_2 and changes made for the campaign at CS2 are discussed next, and Section 4.2.3 discusses how the variations in external CO_2 were used as a filter when selecting data for ventilation measurement.

4.2.1.2 Limitations associated with the calculation of CO_2 difference at UTH and revised approach at CS2

There were several limitations to the calculation of the concentration difference at UTH and efforts were made to improve these for the later measurement campaign at CS2.

The reason for the external HOBO CO_2 sensor drift is unknown. This made accurate calculation of ΔCO_2 challenging, later campaigns at CS2 used an Eltek GD47 sensor (same as the indoor sensors) as these did not exhibit noticeable drift.

Estimating the offset between the outdoor and indoor sensors in situ at UTH meant that the CO_2 sensors were not exposed to the same air during the offset calculation period. The offsets were calculated over 24 hours after the dwelling became unoccupied to effectively eliminate the possibility of elevated CO_2 indoors due to remaining CO_2 from the tracer gas experiments. However, outdoor CO_2 is known to vary diurnally due to photosynthesis (Carrilho et al., 2016). The measurements took place in winter, reducing the effect of photosynthesis, and was calculated over 3 days so the photosynthesis effect will have been largely averaged out.

Nonetheless, a more accurate calculation of the offset between the outdoor and indoor sensors would have been achieved by placing the sensors together so that they were exposed to the same CO_2 concentrations. Such co-location measurements were taken near to the beginning, in the middle and after the campaign at CS2; the mean offset was close to zero and the mean absolute difference was 15 ppm. Small differences in the offsets were observed during different co-location periods (usually close to 10 ppm, with a maximum of 50 ppm). The offset was assumed to linearly move from one offset value to another as at UTH. The uncertainties associated with the calculation of ΔCO_2 is discussed further in Section 4.3.

4.2.2 Spatial homogeneity requirements

As discussed in Section 2.2.3, the tracer gas decay method relies on the assumption that the tracer gas is homogeneously distributed in the measured space. The algorithm applied a criterion regarding the spatial homogeneity of the CO_2 in the measured space, this strictly excluded data which did not meet the required threshold.

The variability of ΔCO_2 concentration during co-location periods at CS2 and in-situ offset estimation at UTH was used to inform the selection of the spatial homogeneity threshold. The standard deviation of concentration difference measurements during co-location periods at CS2 and in-situ estimation of sensor offsets at UTH ranged between 10 and 20 ppm. During the co-location measurements 95% of the concentration difference values fell within two standard deviations of the mean, at the upper end of the standard deviations this was within 40 ppm of the mean.

Additionally, ASTM (2012) recommend that the measured space can be assumed to be spatially homogenous if spatial samples of ΔCO_2 within the measured zone agree within 10%. Given the precision of the sensors as explored during co-location periods discussed above, this was an excessively strict requirement at low ΔCO_2 concentrations, as shown in Figure 4.6a. As a result, the CO_2 in the space was classified as adequately spatially homogeneous if the ΔCO_2 concentrations were within the larger of 40 ppm or 10% of each other[1]. Figure 4.6b shows the periods of data identified as spatially homogeneous based on this requirement during a day of experiments at UTH. The spread in CO_2 concentrations measured by different sensors was taken into account in the calculation of the uncertainty associated with the ventilation rate measurement, this is discussed further in Section 4.3.1.3.

Finally, if the sensor locations were not representative of the air in the measured

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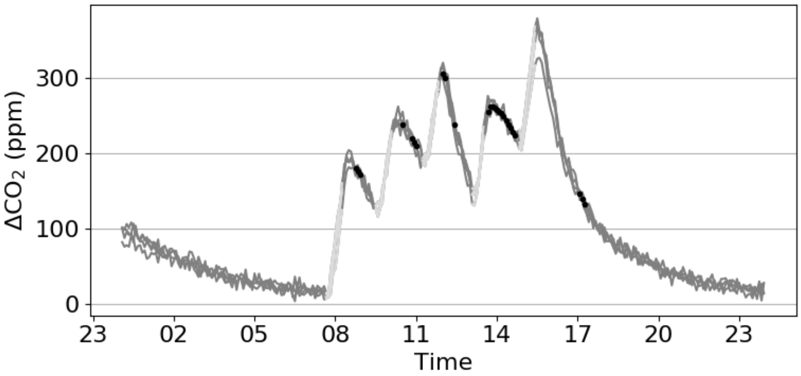
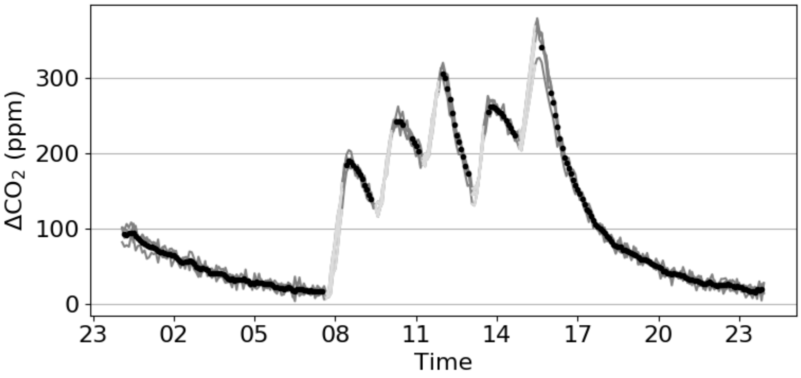
[1] See Sections 5.1.2 and 5.4.1 for discussion of two exceptions to this rule



(a) Spatial homogeneity threshold is 10% of ΔCO_2.



(b) Spatial homogeneity threshold is the greater of 40 ppm or 10% of ΔCO_2.

Figure 4.6: ΔCO_2 data collected in the single measurement room at UTH over a day of experiments, showing the data that meets different spatial homogeneity thresholds. Grey lines show the ΔCO_2 measured by four CO_2 sensors in the single measurement room, light grey lines indicate data collected while the dwelling was occupied and dark grey show unoccupied periods. Black dots indicate that the ΔCO_2 passed the spatial homogeneity threshold.

space then the interpretation that the CO_2 concentration was spatially homogeneous may not be valid. Without the ability to explore CO_2 at all locations, particularly when aiming to monitor in occupied homes, the possibility of the measured locations being unrepresentative remains an unquantifiable uncertainty associated with the measurements. This uncertainty is discussed further in Section 4.3.1.3 along with the results of measurements from four CO_2 sensors in the single measurement room at UTH to explore the effect of sensor placement on measured CO_2 concentration and ventilation rate.

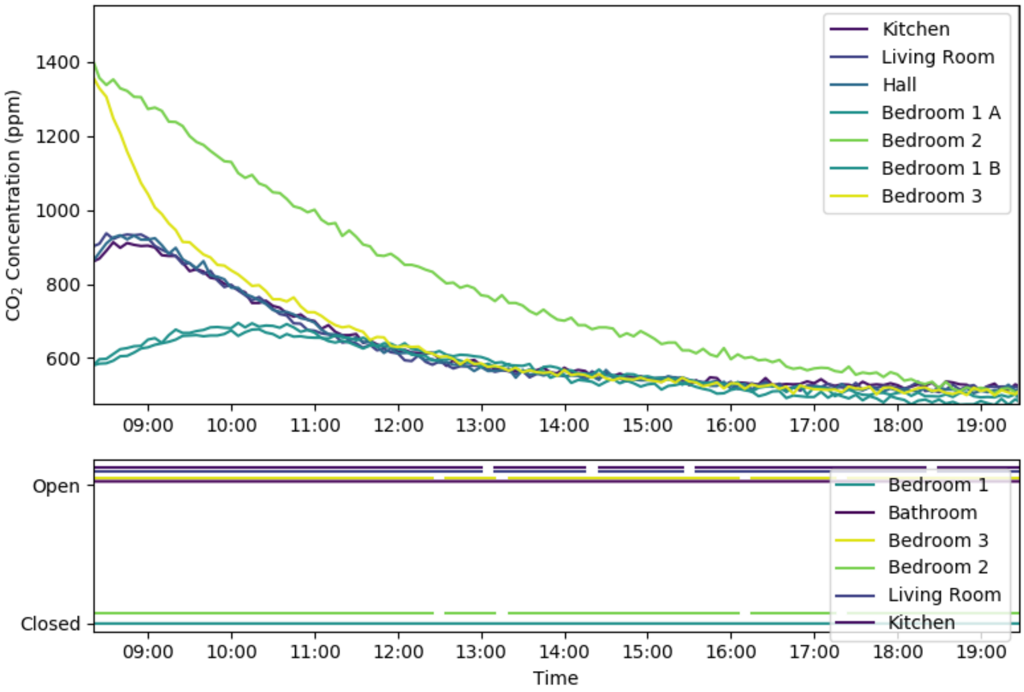


Figure 4.7: The top plot shows the CO$_2$ concentration and the bottom plot shows the status of the doors to rooms in OAF. An unoccupied period is shown in which two doors were closed and different CO$_2$ decays can be clearly seen in different rooms. Note that there were two sensors in Bedroom 1, labelled A and B but shown in the same colour in the figure.

4.2.2.1 Interpreting ventilation in a multi-zone space

The rest of the work presented in this thesis requires that the CO$_2$ data meets the spatial homogeneity threshold just discussed so that the measured space can be considered a uniform single zone during the periods of CO$_2$ decay used for ventilation rate measurement. However, this section briefly discusses what information could be gained from periods of data in which different rooms have different CO$_2$ concentrations.

Figure 4.7 shows an example period of CO$_2$ and door opening data from OAF in which two of the rooms in the flat have their doors closed. In this case the dwelling clearly does not behave as a single zone, so a single ventilation rate does not realistically describe the internal conditions. However, the CO$_2$ concentration decay in different rooms can be used to estimate the ventilation rate in those rooms, with a systematic bias in a known direction. This is an advantage over measurements in which only a single room is measured, or in which the whole house is treated as spatially homogenous. In the example shown in Figure 4.7, Bedroom 2 has higher CO_2 concentration throughout the decay. This room seems to have a lower ventilation rate than the other rooms. The single room ventilation rate calculated using the CO_2 data from Bedroom 2 alone would be systematically larger than the 'true' indoor-outdoor ventilation rate of this room, because some of the decay in CO_2 is likely due to air exchange with the other areas of the dwelling.

Conversely, any ventilation rate calculated for the rest of the flat using the concentration recorded in other rooms would be systematically lower than the 'true' indoor-outdoor ventilation rate of this space. This is because the rate of CO_2 decay in the rest of the flat would be reduced by any exchange of air with higher CO_2 concentration from Bedroom 2.

Analysis of spatially inhomogeneous periods of data was not further explored for this work largely because the participants at CS2 very rarely closed internal doors. However, this example makes clear the importance of the internal doors, in addition to ventilation to the outside, in determining the airflow in a dwelling and highlights why the recording of internal door position during ventilation measurements is important.

4.2.3 Identifying decay periods for analysis

The spatially homogeneous sections of ΔCO_2 data in unoccupied periods were analysed to identify times when the mean ΔCO_2 measured using the indoor sensors in the space of interest was decaying and these periods were split into segments for fitting to the model of ventilation. The following steps were taken to do this:

1. The mean ΔCO_2 data was smoothed to reduce the effect of noise and periods of monotonically decreasing mean ΔCO_2 were identified

2. Mean ΔCO_2 data below a minimum threshold value were ignored such that analysis was not attempted if the noise was significant compared to ΔCO_2

3. Decays were required to have a minimum duration to ensure a reasonable number of points for fitting the ventilation model.

4. Long decays were split into a series of shorter decays so that the driving forces could reasonably be assumed to be constant over the decay period.

5. Decays taking place while external CO_2 varied significantly were rejected.

The five parameters associated with these steps were investigated to assess their effect on the number of decays identified and ventilation rates calculated so that appropriate values could be chosen for the automatic analysis programme. The following subsections discuss each in turn.

In the following analysis the mean ΔCO_2 measured by the sensors in the space of interest was used, for brevity the word mean is omitted and it is made clear where the parameter of interest is the concentration difference recorded by an individual sensor.

4.2.3.1 Smoothing

The unoccupied and spatially homogeneous data were smoothed using a low pass filter in the form of a simple moving average. The smoothed data were used to identify periods in which there was monotonically decreasing ΔCO_2, then the exponential model fitted the non-smoothed ΔCO_2 from this identified period. This section reports on the effect the number of points in the moving average has on the decays identified.

The amount of smoothing was varied between one and nine data points (five to 45 minutes) for the unoccupied, spatially homogeneous data from Flat D at CS2. The corresponding number of decays and several decay rate parameters are shown in Table 4.1.

The number of decays identified more than doubled when smoothing was applied. Figure 4.8 shows a clear period of ΔCO_2 decay which is not found by the algorithm when no smoothing is applied due to noise in the signal: the mean ΔCO_2 does not decrease at each time step although the trend is clearly decaying. Figure 4.8 shows that decays are identified in this period when the mean ΔCO_2 is smoothed over 3 and 5 points. As the number of points ΔCO_2 is smoothed over are increased from zero to nine, the algorithm is increasingly able to identify decays

Table 4.1: The effect of smoothing on the number of decays identified in Flat D's unoccupied, spatially homogeneous ΔCO_2 data, and the mean, maximum and minimum decay rates (h^{-1}) found.

Smoothing	**Number of decays**	**Mean decay rate (h^{-1})**	**Maximum decay rate (h^{-1})**	**Minimum decay rate (h^{-1})**
None, 5 minutes	73	0.55	1.07	0.21
3 points, 15 minutes	176	0.44	1.07	0.10
5 points, 25 minutes	220	0.40	1.07	0.01
7 points, 35 minutes	246	0.37	1.07	0.05
9 points, 45 minutes	254	0.36	1.07	0.02

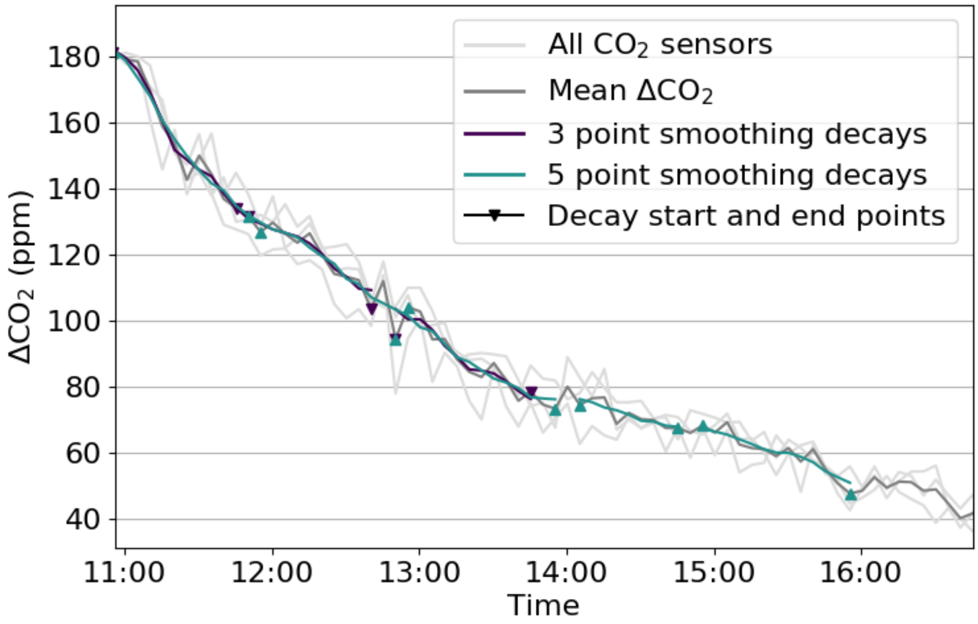


Figure 4.8: Showing ΔCO_2 during an unoccupied period in Flat D at CS2. The graph shows the periods of data that are identified to be used in the exponential decay models when different amount of smoothing are applied to the mean ΔCO_2 data. When no smoothing is applied none of this section of data is identified as appropriate for ventilation rate analysis.

associated with smaller differences in ΔCO_2 and corresponding lower ventilation rates, as shown in Table 4.1. Smoothing over 3 data points (15 minutes) for decay identification was chosen as a trade-off between analysing excessively noisy decays by increasing the number of smoothing points and identifying few decays by not applying any smoothing.

Table 4.2: The effect of the minimum allowed ΔCO_2 on the number of decays identified in Flat D's unoccupied, spatially homogeneous ΔCO_2 data, and the mean, maximum and minimum decay rates found.

Minimum ΔCO_2 (ppm)	**Number of decays**	**Mean decay rate (h^{-1})**	**Maximum decay rate (h^{-1})**	**Minimum decay rate (h^{-1})**
0	219	0.48	1.25	0.10
25	209	0.46	1.43	0.10
50	176	0.44	1.07	0.10
75	139	0.44	1.07	0.10
100	100	0.45	1.00	0.10
125	82	0.46	1.01	0.13

4.2.3.2 Minimum ΔCO_2 threshold

The algorithm included a minimum ΔCO_2 threshold below which the data was discounted for the purposes of identifying decays. Table 4.2 summarises the decay rate results when this threshold is varied between 0 ppm and 125 ppm. The data used to investigate this effect were the unoccupied and spatially homogeneous data from Flat D. At low ΔCO_2 concentrations this flat showed some possible instances of CO_2 leaking from nearby dwellings so the effect of the threshold was particularly important in this case.

Table 4.2 shows little difference in the mean, maximum and minimum decay rates calculated with different minimum ΔCO_2 thresholds. Nonetheless, the data collected during the co-location of all CO_2 sensors showed the standard deviation of the difference between any of the sensors and the outdoor sensor was between 10 ppm and 20 ppm (see Section 4.2.2 further discussion of this), a threshold above this has therefore been applied.

Additionally, as mentioned above, an investigation of the ΔCO_2 data during unoccupied times in this flat and others revealed probable leakage of air between adjacent flats. Leakage of air from neighbouring flats is discussed further in Section 4.3.2 with reference to the unquantifiable uncertainties associated with the measurement results. Figure 4.9 shows that the mean ΔCO_2 settles at around 50 ppm during a series of unoccupied periods in Flat D, this trend was uncommon but not unique. Similar artefacts were found in the data from the other flats to differing degrees, likely related to the extent of leakage between individual flats, leakage pathways,

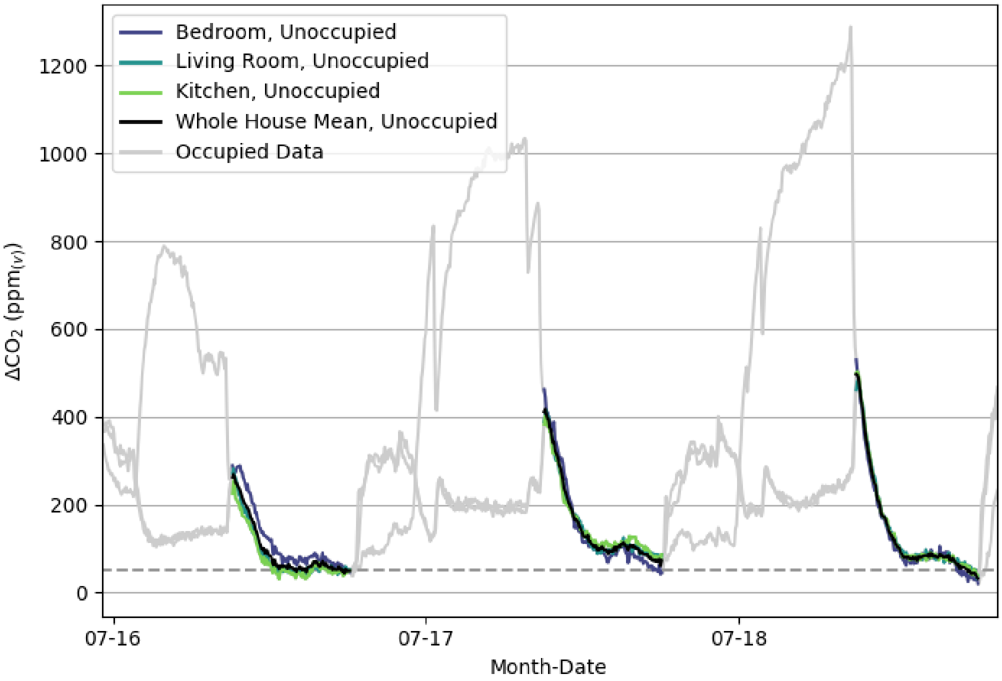


Figure 4.9: Showing three days of ΔCO_2 data in flat D. The grey dashed line shows 50 ppm.

occupancy patterns in adjacent flats and ventilation rates in each of the flats. At times when CO_2 is leaking from adjacent flats the decay results will be systematically skewed towards lower ventilation rate values, this effect will be larger at lower ΔCO_2. However, without extensive monitoring in neighbouring flats it is not possible to robustly differentiate between this and legitimate low air exchange with outdoors.

In light of the standard deviations during co-location and the possibility of leakage from adjacent flats, a threshold of 50 ppm was chosen. This enables a large number of decays to be recorded, without the expectation of significant bias due to leakage from adjacent flats, although the extent of this bias cannot be quantified.

4.2.3.3 Minimum and maximum decay length

In analysis of tracer gas concentration decay it is assumed that the ventilation rate is constant over the period during which the tracer gas concentrations are fitted to an exponential decay, as discussed in Section 2.2.3.3.2. The time scales of this assumption vary considerably in the literature, from minutes (Cui et al., 2015) to 8-hours in an extreme case (Parsons, 2014). Limits were placed on the minimum and maximum decay time used to measure ventilation rates, the minimum decay length is discussed next.

4.2.3.3.1 Minimum decay length The minimum number of decay length was varied between 20 minutes and 60 minutes for the spatially homogeneous periods of unoccupied data in Flat A at CS2, Table 4.3 shows the effect of this on the number of decays identified and the properties of the decay rates. This dataset was chosen as the windows were very often open in this dwelling and the ventilation rates were often high, meaning that ΔCO_2 was likely to reduce to close to zero quickly in this flat. The minimum length of decay time combined with the ΔCO_2 concentration at the start of the decay determine the maximum measurable ventilation rate. This is because decays that fall below the minimum ΔCO_2 threshold (discussed in the previous section) faster than the minimum decay time are not analysed. Table 4.3 shows the maximum measurable ventilation rate if the decay starts with a ΔCO_2 concentration of 600 ppm and falls to the 50 ppm (the minimum ΔCO_2 threshold) for different minimum decay times.

The data presented in Table 4.3 show that a 20-minute minimum decay length gives the lowest minimum ventilation rate. This result is not expected since low ventilation rates will tend to result in long decays, but could be because short decays are more readily influenced by noisy signals since there are fewer points fitted by the least squares algorithm. A minimum decay length of 20 minutes means that only four data points are used by the least squares algorithm to estimate the decay rate, reducing the degrees of freedom to two.

Table 4.3 also shows the mean and maximum ventilation rates decrease with longer minimum decay lengths. This is likely because decays taking place when the ventilation rate is higher will be shorter, so fewer are identified when the minimum decay time is longer. Also, increasing minimum decay length beyond 40 minutes significantly reduces the number of identified decays in Flat A. A minimum decay time of 40 minutes was chosen as this identified a reasonable number of decays in

Table 4.3: The effect of the minimum decay length on the number of decays identified in Flat A's unoccupied, spatially homogeneous ΔCO_2 data, and the mean, maximum and minimum decay rates (h^{-1}) found. The final column shows the ventilation rate if the ΔCO_2 concentration dropped from 600 ppm to 50 ppm in the minimum decay time.

Minimum decay time (minutes)	Number of decays	Mean decay rate (h^{-1})	Maximum decay rate (h^{-1})	Minimum decay rate (h^{-1})	Decay from ΔCO_2 = 600ppm to ΔCO_2 = 50 ppm (h^{-1})
20	85	1.1	2.7	0.2	7.5
40	34	1.0	2.5	0.3	3.7
60	16	0.7	1.3	0.3	2.5
80	11	0.6	1.3	0.3	1.9

high-ventilation rate flats, the decay model was fitted with at least 8 data points and the maximum measurable ventilation rate was still above the maximum ventilation rate measured with a shorter minimum decay time.

4.2.3.3.2 Maximum decay length As discussed, one of the key assumptions of the tracer gas decay technique is that the ventilation rate is constant for the duration of the period over which the decay is analysed. Without implementing a maximum decay time the longest decays at UTH and CS2 were over eight hours long; it is very unlikely that driving forces affecting the ventilation rate would be constant over such a long period.

The goodness of fit with increasing decay time was analysed using the Durbin-Watson statistic. The Durbin-Watson statistic can be used to characterise the degree of autocorrelation in the residuals (Hughes and Hase, 2010), considerable autocorrelation indicates incorrect specification of the model. The statistic is calculated as follows:

$$D = \frac{\sum_{i=2}^{N}(R_i - R_{i-1})^2}{\sum_{i=1}^{N}(R_i)^2}, \tag{4.3}$$

where D is the Durbin-Watson statistic, N is the number of data points in the fit and R_i is the i^{th} residual. A Durbin-Watson value of 2 indicates that the model describes the data well. A result tending towards 0 indicates systematic correlation between successive residuals and a result tending towards 4 indicates systematic anti-correlation in successive residuals.

Figure 4.10 shows the Durbin-Watson statistic against length of decay for the data from Flat D at CS2. The figure clearly shows that without imposing a maximum decay length there is trend towards decreasing Durbin-Watson value with

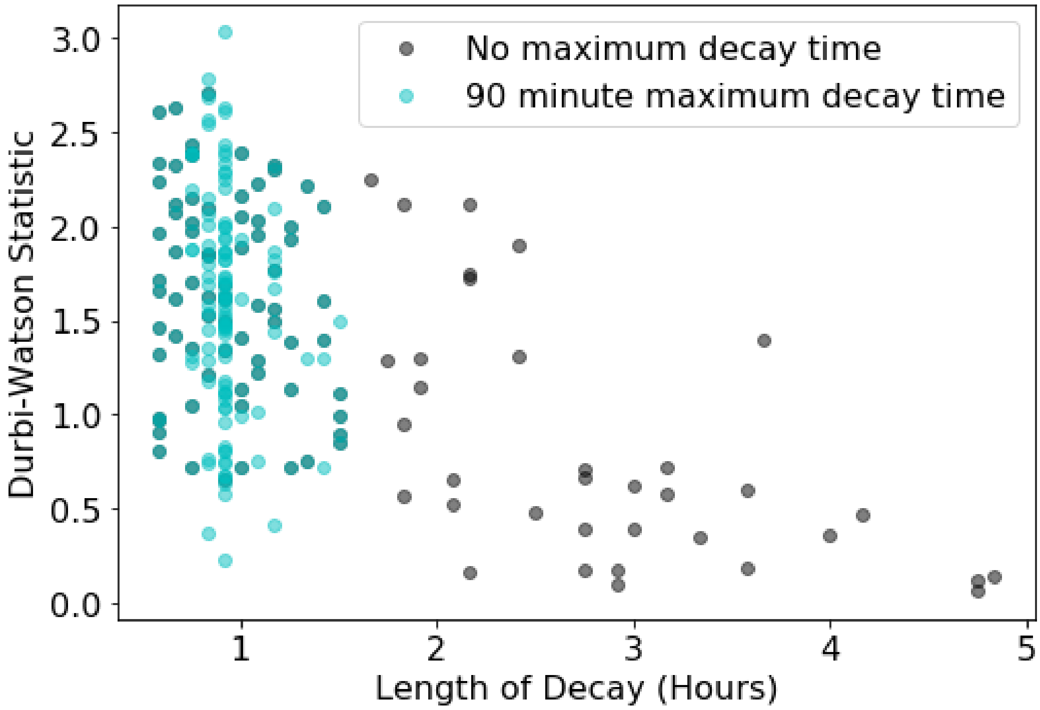


Figure 4.10: Durbin-Watson test statistic against length of decay when decays are limited to a maximum period of 90 minutes and when there is no maximum decay time using data from Flat D at CS2.

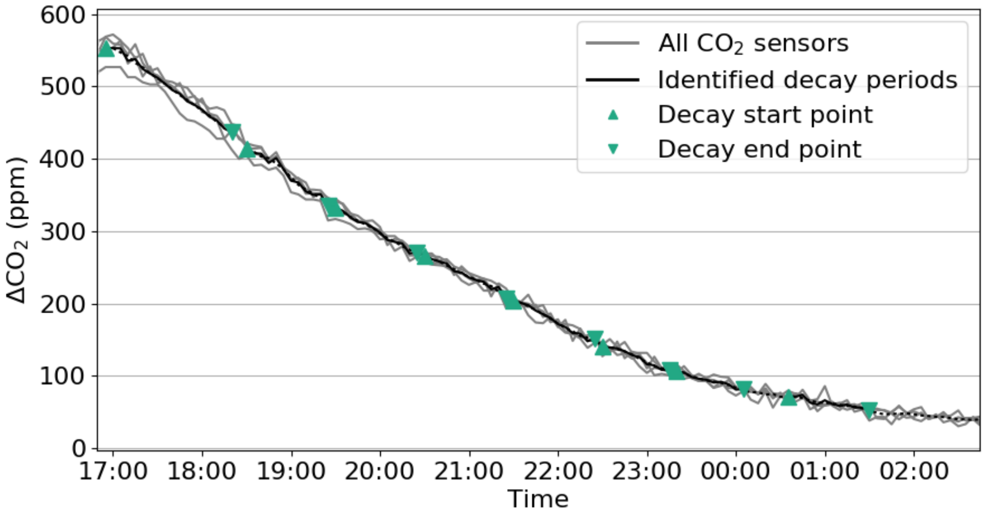


Figure 4.11: Example long ΔCO_2 decay from data collected at UTH. The figure shows how the decay was split into several shorter decay periods for fitting to the exponential decay ventilation model.

increasing length of decay, this indicates that when decays are long the model often does not describe the data well. According to Etheridge and Sandberg (1996) wind speeds and pressures averaged over approximately an hour may be considered constant for the purposes of analysing ventilation driving forces. Additionally, the wind data from Midas has hourly intervals (described in Section 3.6.1) and was used to analyse the effect of driving forces on the ventilation rate was hourly (the effect of driving forces is discussed in the following chapter). Therefore, long decays were split into a series of hour-long periods to be analysed, the final decay in the series was allowed to be up to 90 minutes long or was split into two equal length decays if it was longer than 90 minutes. Figure 4.11 shows how the data was divided into periods to be analysed in the case of a long decay. The Durbin-Watson values after imposing these breaks indicate that the model generally shows less autocorrelation suggesting a better fit of the model to the data, as shown in Figure 4.10.

4.2.3.4 Variability in external CO_2 during the decay period

The above analysis for identifying appropriate periods of decay for ventilation rate measurement has not considered the possibility of variation of external CO_2 affecting the measurements. However, any CO_2-based tracer gas analysis substitutes the tracer gas concentration in the mass balance equation with the concentration difference between inside and outside and therefore implicitly assumes that the concentration terms can be substituted with with $\Delta CO_2(t) = CO_{2,int}(t) - CO_{2,ext}$. The external CO_2 is assumed to be stable, such that $\Delta CO_2(t)$ varies only with the internal CO_2 concentration. However, as discussed in Section 4.2.1, the urban CO_2 dome is an established phenomenon in atmospheric science (Xueref-Remy et al., 2018), so urban CO_2 concentrations are known to be variable diurnally and seasonally. Additionally, Carrilho et al. (2016) developed a method using variation in daily variation in external CO_2 concentration to measure ventilation rates. As highlighted in Section 3.2.2, simultaneous measurements of external CO_2 during tracer gas measurement periods is rare. This section quantifies the effect of assuming a constant outdoor CO_2 concentration during ventilation measurements at UTH and justifies a limit on the extent of external CO_2 variation tolerated for ventilation measurements

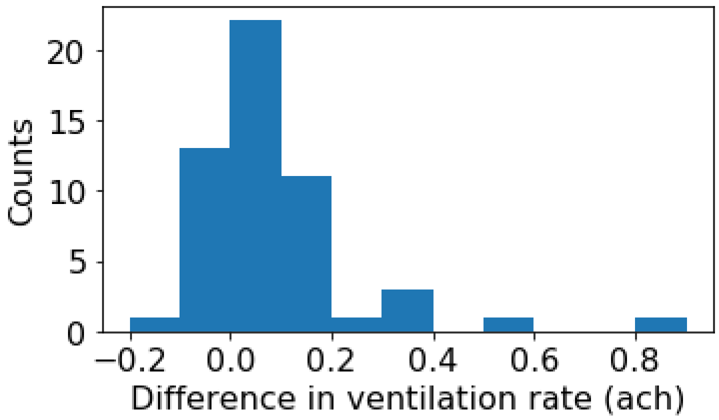


Figure 4.12: Histogram of the difference in calculated ventilation rates when the measured external CO_2 is used to calculate ΔCO_2 compared to using a constant background CO_2 concentration to calculate ΔCO_2.

at UTH after the installation of the external sensor and for all measurements at CS2.

After the external CO_2 sensor was installed at UTH two rooms were used for measurements and 53 single room ventilation rates were measured. These rooms contained several sensors and the mean ΔCO_2 measured by these sensors was used to calculate the ventilation rate. The ventilation rate was calculated for each decay using the assumption of a static external CO_2 concentration and the measured external concentration to calculate ΔCO_2 (both ΔCO_2 calculations were described in the Section 4.2.1). Figure 4.12 shows a histogram of the difference between the ventilation rate calculated using each method of accounting for external CO_2. The median difference was 0.04 ach, the distribution of differences was clearly not Gaussian and some measurements were much more affected than others. The difference in the calculated values was over 0.2 ach for 11% of the measurements and over 0.1 ach in 32% of measurements. The difference between the ventilation rates calculated with or without measuring outdoor CO_2 is significant in terms of the frequency with which such events occur and the interpretation of the ventilation rate calculated.

Figure 4.13 shows a period of data in which the ventilation rates calculated during the two periods identified differed by over 0.2 ach depending on which method of ΔCO_2 calculation was used. During the period shown in Figure 4.13 the external

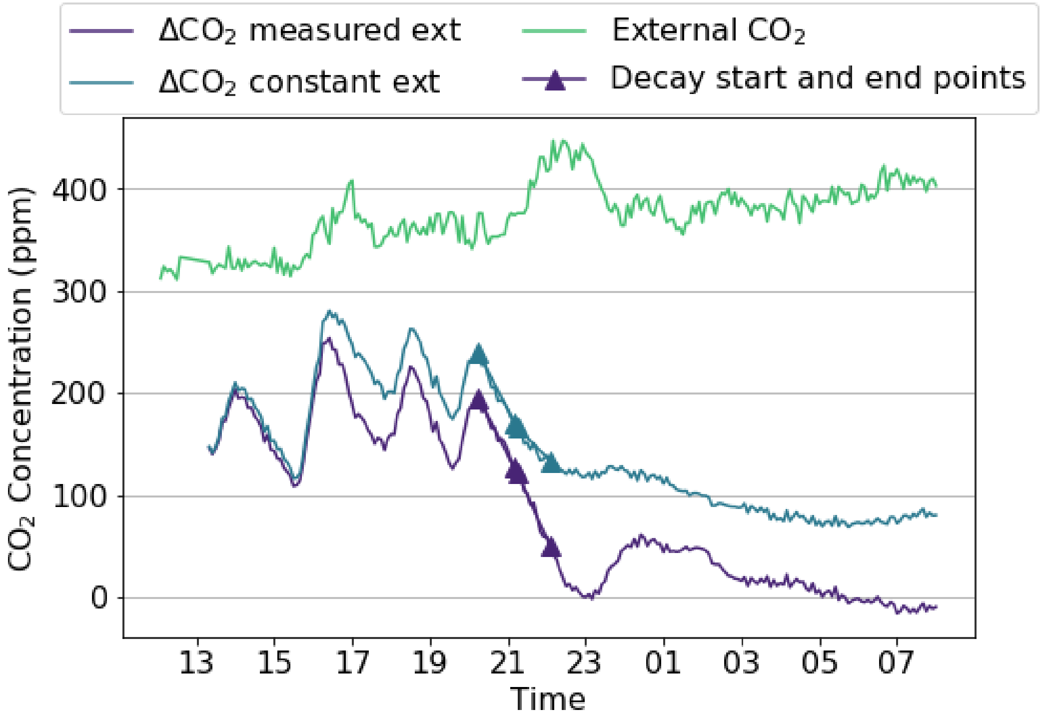


Figure 4.13: Showing ΔCO_2 calculated using a constant value for the external CO_2 and ΔCO_2 calculated using the measured external CO_2 concentration, also showing the measured external CO_2 concentration. The ventilation rates calculated during the two periods identified with the triangular markers differed by over 0.2 ach depending on which method of ΔCO_2 calculation was used.

CO_2 concentration varies by over 100 ppm and there is a steep rise between 21:00 and 23:00. During the identified decay periods the external CO_2 concentration is rising, so ΔCO_2 calculated using the measured outdoor CO_2 falls towards zero much more quickly than would be assumed by using a constant outdoor concentration. Cases where the difference in ventilation rate was over 0.1 ach depending on the method of accounting for external CO_2 were investigated in detail, these showed similar but less extreme rises in external CO_2 compared to that shown in Figure 4.13.

The impact of the ΔCO_2 calculation method on the measured ventilation rate will vary depending on factors including the magnitude of the concentration difference during the decay, the magnitude of the 'true' ventilation rate and the rate of change of the external CO_2 concentration. Since these measurements took place in a test dwelling subjected to variable weather conditions as well as variable outdoor

Table 4.4: Proportion of decays rejected due to large variation in external CO_2 concentration for each of the case study dwellings.

	UTH: Back room	**UTH: Bedroom**	**Flat A**	**Flat B**	**Flat C**	**Flat D**
Rejection rate	28%	46%	17%	9%	16%	4%

CO_2 concentrations it was not possible to isolate the measurement uncertainty due to the use of a static background CO_2 concentration. However, these values give an impression of the size of the effect on the calculated air change rate when the outdoor concentration is not measured.

Variations in external CO_2 violate the decay technique assumption that there are no sources of tracer gas, so a limit was placed on the external CO_2 variation allowed for a decay to be considered valid. The findings above show that this can have a significant impact on the measured ventilation rate result, and the evidence from literature relating to the variation of CO_2 concentration in urban CO_2 domes shows that variation in external CO_2 concentration is a common phenomenon. Selection of the threshold drew on the co-location data from CS2 and the in-situ estimation of sensor offsets at UTH which showed that the standard deviation of the estimated zero ΔCO_2 ranged between 10 and 20 ppm. A threshold of 40 ppm variation in the external CO_2 concentration was applied, which relates to two of the maximum standard deviations. This threshold was applied to the data during the decay and in the hour preceding the decay since changes in external CO_2 take time to affect internal concentrations. For Figure 4.13 the external CO_2 variation during the decay and the preceding hour was 36 ppm and 85 ppm for the first and second decays respectively. The first decay in Figure 4.13 meets the required threshold of external CO_2 variation and the ventilation rate for this decay varies by 0.1 ach depending on which ΔCO_2 method is used. This is because the external CO_2 is fairly constant but higher than usual so that ΔCO_2 calculated using the constant background gives higher than appropriate values and a consequently lower ventilation rate.

Table 4.4 reports the proportion of decays which were rejected due to variation in external CO_2 for each of the case study dwellings, the data for UTH does not include measurements taken prior to the installation of the external sensor. The proportion of rejected decays is particularly high at UTH, this could be because the external sensor was in place from the end of November 2018 until the beginning of February 2019, aligning with colder months when the variation in external CO_2 due to urban emissions is expected to be greater. Clearly, measurements at UTH prior to the installation of the external sensor could have been affected by changes in external CO_2 concentration, although these measurements took place during autumn (September to November) so it is expected that fewer results were significantly affected. Nonetheless, this remains and unquantifiable source of uncertainty related to these results.

At all of the case study dwellings the number of decays affected is significant and highlights the importance of measurement of external CO_2 during CO_2 based tracer gas measurements.

4.2.3.5 Identification of decays for ventilation rate analysis summary

The decay finding algorithm has been designed to find appropriate periods of ΔCO_2 for ventilation rate analysis. This section has discussed the effect of parameters in the decay-finding algorithm on the number of decays identified and the properties of the decay rates calculated from those decays. The parameters discussed in this section interact with each other to influence the number and type of decays identified, for example increasing the smoothing at the same time as decreasing the minimum ΔCO_2 would increase the number of decays identified compared to changing only one parameter. Nonetheless, this section has shown that the combination of thresholds applied by the algorithm results in the identification of reliable decays. In applying this method in different scenarios (different buildings, locations, equipment, etc.) it would be necessary to assess whether the thresholds applied should be modified.

4.2.4 Calculating the ventilation rate

The periods identified by the analysis of the ΔCO_2 data described above were used to calculate the ventilation rates. The un-smoothed ΔCO_2 data from these periods was fitted to the ventilation model. The un-smoothed data was used so that the data were not influenced by data originating outside of the decay period.

Equation 3.1 was linearised and the ΔCO_2 values were fitted to the following model using weighted least squares algorithm (Numpy's polyfit algorithm (Harris et al., 2020)):

$$ln(\Delta CO_2(t)) = -At + k, \tag{4.4}$$

where, as above, $\Delta CO_2(t)$ is the mean difference between the indoor and outdoor CO_2 concentration measured by each of the sensors in the measured space at time t since the start of the decay period. The constants A and k are fitted by the least squares algorithm. k is the fitted $ln(\Delta CO_2)$ at the beginning of the decay and A is the fitted air change rate. The least squares fitting was weighted according to the uncertainty in the ΔCO_2 value at each time step based on the spread in $\Delta CO_2(t)$ measured by each of the CO_2 sensors contributing to the calculation of the mean $\Delta CO_2(t)$. Further details of uncertainty and weighting is discussed in Section 4.3.

Figure 4.14 shows an example of an identified decay from the data collected at UTH and the fitted model, along with the residuals and a lag-plot of the residuals. Parameters including root mean square error and the Durbin-Watson statistic (discussed in the previous section) were calculated along with the ventilation rates so that the goodness of fit could be assessed.

4.3 Uncertainty of the calculated ventilation rates

The above sections have described how CO_2 data was analysed to give measurements of ventilation rate. It is essential to report the uncertainty on a measured value (Hughes and Hase, 2010) and this section discusses the uncertainty associated with ventilation rate measurement in this work. The uncertainty of a measurement ‘characterises the dispersion of values that could reasonably be attributed to

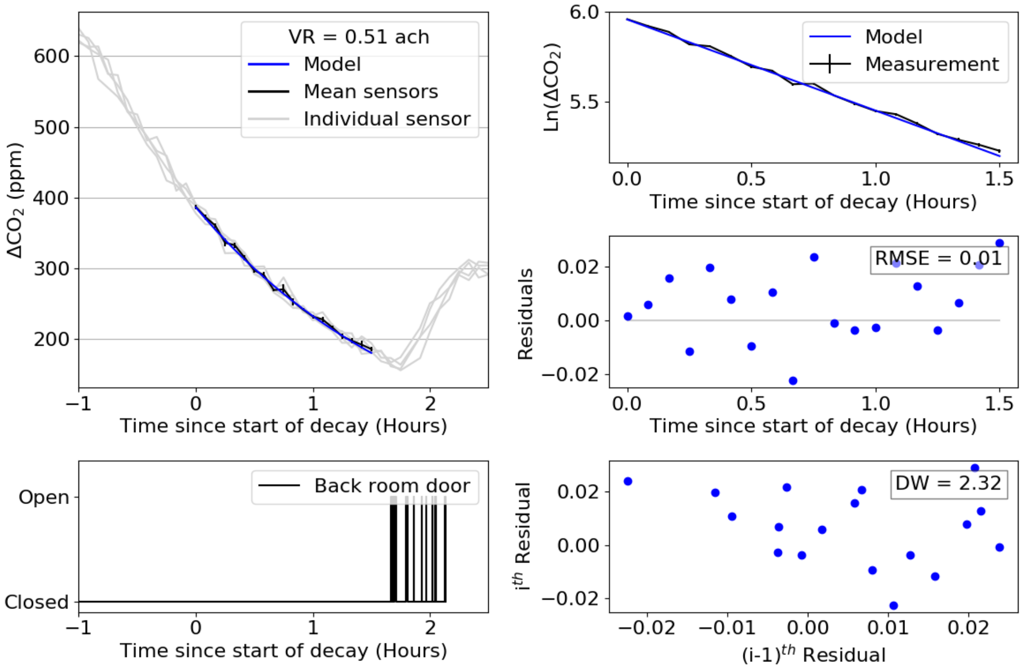


Figure 4.14: Example ΔCO_2 decay in the single measurement room at UTH. The top left hand plot shows the ΔCO_2 concentrations with the error bars on the mean ΔCO_2 representing the standard uncertainty in the spread of ΔCO_2 values. The ventilation rate (VR) is given in the upper right corner. The top right plot shows the natural logarithm of the mean ΔCO_2 and the fitted linear model. The middle and bottom plots on the right show the residuals and a lag plot of the residuals respectively; the root mean square error (RMSE) and Durbin-Watson statistic (DW) are given in the upper right corner of the middle and bottom plot respectively. The bottom left plot shows the status of the door to the measurement room.

the measurand' JCGM (2008, p. 2), where the measurand is the particular quantity subject to measurement. This is in contrast with the error which is the difference between the measured value and the true value, and is thus unknowable (JCGM, 2008). Although the terms error and uncertainty are often discussed as though they are synonymous the following will strictly use the above distinction.

Quantifiable, unquantifiable and unknown effects all contribute to uncertainty in measurement (JCGM, 2008). The quantifiable elements of the uncertainty associated with ΔCO_2 measurement and how this is related to uncertainty in the estimated ventilation rates is discussed in the following section, followed by discussion of the quantifiable uncertainty associated with the measurement of CO_2 concentration and associated with the spatial inhomogeneity. Unquantifiable uncertainties are then discussed in Section 4.3.2, including discussion of definitional uncertainty, uncertainty arising from an imperfect translation between the concept of ventilation and the measurand and the possibility of flows from adjacent spaces.

4.3.1 Quantifiable uncertainty in the measurement of ventilation rate

Ventilation rate is not a static property but varies depending on the temperature difference, wind profile and configuration of various openings in the envelope. The spread in the calculated ventilation rate values therefore do not represent the uncertainty because we do not expect the same ventilation rate during each measurement period. This means that each measurement of the ventilation rate should have its own uncertainty attributed to it.

According to JCGM (2008), evaluation of measurement uncertainty can take place via a statistical means (type A evaluation), in which a series of repeated measurements is used, or via other means (type B evaluation). Type B evaluation may include information gathered from previous measurements, manufacturer's specifications, calibration data or uncertainties quoted for reference data taken from handbooks. In both cases an estimate is placed on the standard uncertainty of measurement, this is the estimated standard deviation associated with the measurement result. If the measurand is not measured directly, then the uncertainty of the input variables are used to calculate the standard uncertainty of the measurand. In the present case this means that the uncertainty associated with the ventilation rate is calculated via estimations of the uncertainty in ΔCO_2. The following section describes how the uncertainty in ΔCO_2 was propagated to uncertainty in the ventilation rate, and the sections following this present the estimations of quantifiable uncertainty in ΔCO_2 attributable to sensor uncertainty and spatial inhomogeneity of CO_2 in the measured space and the associated uncertainty in estimated ventilation rates.

4.3.1.1 Propagation of ΔCO_2 uncertainties to ventilation rate uncertainty

As described in Section 4.2.4 the ventilation rate is calculated via a weighted least squares fit to a linearised model of exponential decay. Once the uncertainty in ΔCO_2 has been estimated the uncertainty in $ln(\Delta CO_2)$ is given by (Hughes and Hase, 2010):

$$\alpha_{ln(a)} = \frac{\alpha_a}{a}, \tag{4.5}$$

where $\alpha_{ln(a)}$ is the uncertainty in $ln(a)$, and in the present case a is ΔCO_2. Following Hughes and Hase (2010) the least squares fit is weighted by the inverse square of this uncertainty on $ln(\Delta CO_2)$.

The ventilation rate is given by the gradient of the linear model as outlined in Section 4.2.4. The uncertainty associated with the gradient of a weighted linear least squares fit is given by (Hughes and Hase, 2010):

$$\alpha_m = \sqrt{\frac{\sum_i w_i}{\sum_i w_i \sum_i w_i x_i^2 - (\sum_i w_i x_i)^2}}, \tag{4.6}$$

where α_m is the uncertainty in the gradient of the least squares fit (the ventilation rate in this case), $w_i = \alpha_i^{-2}$ where α_i is the uncertainty in the dependent variable of the i^{th} point in the fit (the uncertainty on $ln(\Delta CO_2)$ in this case), the summations are over all data points in the least squares fit and x is the independent variable (time elapsed since the start of the decay in this case).

The following sections describe how the uncertainty associated with ΔCO_2 measurement and spatial inhomogeneity of CO_2 in the measured spaces were quantified, such that they could be substituted into the above equations to give estimates of the uncertainty in the measured ventilation rates.

4.3.1.2 Uncertainty in measurement of CO_2 concentration and ΔCO_2

Consideration was given to estimating the uncertainty of the ΔCO_2 measurement by non-statistical (type B) evaluation. The Eltek GD47 (which was used for all CO_2

measurements except the outdoor measurements at UTH) data-sheet stated an accuracy for the CO_2 sensor of 50ppm + 3% of the measured value. During discussion with the UK partner of the manufacturer of the EE 893 CO_2 sensor within the Eltek GD47 the quoted accuracy was stated to be a 'worst case' deviation from the true CO_2 value, taking into account possible variations in airflow rates, temperature and contaminants (personal communication). They expected the repeatability to be much better than this, especially in a building in which the CO_2 concentration is not likely to increase or decrease at extremely high rates. This value was not intended to, and not likely to, represent the standard uncertainty of the CO_2 concentration measurement in a building.

Additionally, the absolute value of the concentration was not critical for the calculation of the ventilation rate since the CO_2 difference was used in the calculation (Etheridge, 2012). In this context, the precision of the concentration measurement and the estimate of the offset between CO_2 sensors is important, both of these parameters were estimated by statistical means.

4.3.1.2.1 Precision of CO_2 concentration measurements. The precision of the CO_2 concentration values was estimated for three of the Eltek-GD47 sensors. The CO_2 concentration measurements from each sensor at each time t are single measurements of the concentration at the location of the individual sensor at the measurement time. The standard deviation of a measurement can be considered as the uncertainty of a single measurement (Taylor, 1997), therefore data was collected to empirically estimate the uncertainty of a single measurement. To estimate the standard deviation of CO_2 concentration measurement using the Eltek GD-47 sensors three sensors were co-located in an office for three days and set to record concentration readings every 10 seconds. The maximum measurement frequency for these sensors was 15 seconds, so the recorded data was downsampled to 20-second intervals to ensure unique measurements were reported at every data point. The standard deviation of CO_2 concentration in each five minute period was calculated (since all other CO_2 data for this project was collected at 5 minute intervals). The mean standard deviation of the CO_2 concentration in these periods was 5.4 ppm and this was taken as an estimate of the uncertainty of a single CO_2 concentration measurement.

The data were recorded in an office building from Friday afternoon to Monday morning since a controlled CO_2 environment was not available, the data included a CO_2 decay after people left the office on Friday and CO_2 build-up on Monday morning. This means that the calculated value is likely to be an over-estimate of the uncertainty in a single measurement since the CO_2 was not held constant throughout the measurement period and variations in each 5 minute period will be due to real changes in the CO_2 concentration as well as random fluctuations. Nonetheless, this is a small value so a more detailed characterisation is not necessary.

4.3.1.2.2 Uncertainty associated with the offset between sensors. The uncertainty associated with the offset between the indoor sensors and outdoor sensor was estimated using co-location data. All sensors were placed next to each other (as described in Section 4.2.2) and the mean difference between each of the sensors usually indoors and the sensor usually outdoors was calculated. The uncertainty of the mean value associated with repeat measurements of a measurand is given by (Taylor, 1997):

$$\alpha_b = \frac{\sigma_b}{\sqrt{N_b}}, \tag{4.7}$$

where α_b is the standard uncertainty of the estimate of the mean value of b, σ_b is the standard deviation of the measured values of b and N_b is the number of repeat measurements of b. In the present case b was the measurement of the offset, k_i, between the outdoor sensor and each indoor sensor.

The sensors were co-located near the beginning, in the middle and after the measurement campaign at CS2. During these three periods, the values of α_{k_i} were similar and varied between 0.2 and 0.6 ppm. For UTH, as described in Section 4.2.2, the offsets were estimated while the sensors were in-situ, the standard uncertainty in the offsets calculated at UTH during the comparison period were close to 0.6 ppm for all sensors.

However, the mean values of k_i were different when calculated in different co-location periods at CS2 and at UTH the outdoor sensor was observed to drift significantly. As explained in Section 4.2.1 a linear drift in the offset values was assumed between co-location or in-situ offset estimation periods. A linear drift in offset between the sensors at UTH appeared to describe the data well since in using this model the ΔCO_2 data recorded close to zero CO_2 difference when UTH had been unoccupied for prolonged periods. At CS2 a linear drift in the offsets has been assumed as this was appropriate at UTH, although the change in offsets over time was small so this will not have contributed significantly to the uncertainty.

The influence of temperature and pressure on CO_2 concentration measurements were discussed in Section 3.6.1. These were not likely to cause significant uncertainty and have been ignored for the purposes of the uncertainty calculations given in this chapter.

4.3.1.2.3 Combining sensor uncertainties and associated ventilation rate uncertainty. The mean ΔCO_2 values used in the least squares fit can be calculated in the following manner:

$$\Delta CO_2 = \frac{\sum_i (CO_{2,i} - k_i)}{N} - CO_{2,outdoor}, \tag{4.8}$$

where the first term on the right is the mean of the corrected indoor CO_2 concentrations (the uncertainty associated with the spatial inhomogeneity measured by these sensors is discussed in the following section). The summation is over all indoor sensors in the space of interest and N is the number of indoor sensors in the space of interest.

A standard propagation of uncertainty in each of the terms (Hughes and Hase, 2010) gives the following equation for the combined uncertainty in ΔCO_2 due to sensor uncertainty:

$$\alpha_{\Delta CO_2,sensor} = \sqrt{\sum_i \left(\frac{1}{N} \sqrt{\alpha^2_{CO_{2,i}} + \alpha^2_{k_i}} \right)^2 + \alpha_{CO_{2,outdoor}}}, \tag{4.9}$$

where N and i are as above, $\alpha_{CO_{2,i}}$ and $\alpha_{CO_{2,outdoor}}$ are taken to be the uncertainty associated with a single measurement of CO_2 as described above (5.4 ppm). α_{k_i} is the uncertainty associated with the measurement of the offset as described above. This value very small compared to $\alpha_{CO_{2,i}}$, between 0.2 ppm and 0.6 ppm, so a

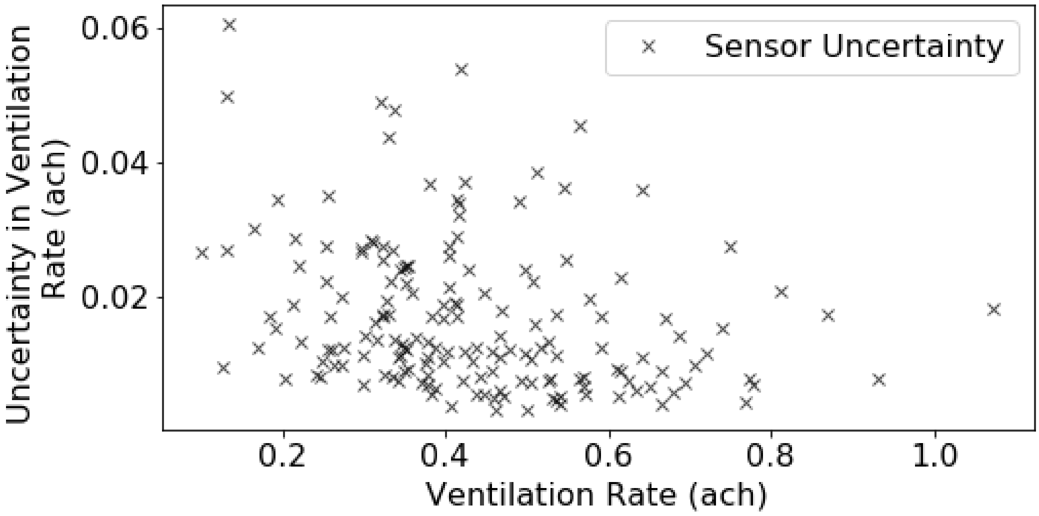


Figure 4.15: Ventilation rates measured in Flat D at CS2 against the uncertainty in these ventilation rates due to the uncertainty associated with CO_2 sensor uncertainty

Table 4.5: The mean and standard deviations of the uncertainty due to measurement of CO_2 concentration calculated for ventilation measurements at each of the case study dwellings.

	UTH: Back room	**Flat A**	**Flat B**	**Flat C**	**Flat D**
Mean uncertainty (ach, %)	0.01, 4	0.03, 3	0.01, 3	0.02, 4	0.02, 5
Standard deviation of uncertainty (ach, %)	0.01, 4	0.01, 2	0.01, 3	0.01, 4	0.01, 6

blanket value of 0.6 ppm was used in the analysis as a conservative estimate.

This uncertainty was propagated forward to give uncertainties on the calculated ventilation rates as described above (Section 4.3.1.1). Figure 4.15 shows this uncertainty in the ventilation rate against the ventilation rates measured in Flat D at CS2, this shows no clear relationship with the magnitude of the measured ventilation rate. Table 4.5 shows the mean and standard deviations of the uncertainties due to sensor uncertainty are small for all case studies.

The uncertainty calculated in this section relates to the precision attributed to measurements of ΔCO_2 by individual CO_2 sensors, however the spatial inhomogeneity of the measured space is not taken into account. This is important given the spatial homogeneity requirement discussed in Section 4.2.2 that measurements in the space of interest be within the larger of 10% of the measured ΔCO_2 concen-

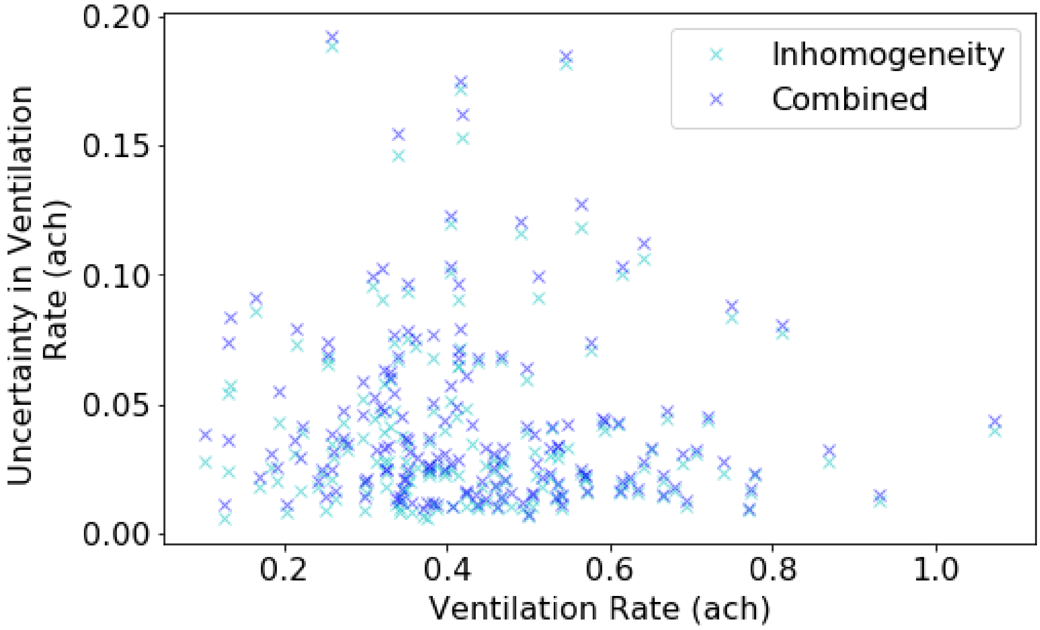


Figure 4.16: Ventilation rates measured in Flat D at CS2 against the uncertainty in these ventilation rates due to the inhomogeneity of CO_2 in the measured space and the combined uncertainty due to spatial inhomogeneity and sensor uncertainty.

tration or 40 ppm. The following section quantifies the uncertainty associated with spatial inhomogeneity in the space.

4.3.1.3 Uncertainty due to spatial inhomogeneity

Multiple CO_2 sensors were used for all ventilation measurements at UTH and CS2 and the mean ΔCO_2 difference was calculated using all sensors in the relevant space. Since multiple measurements of ΔCO_2 were taken, Equation 4.7 could be used to calculate the standard uncertainty on ΔCO_2. Where N_b is now the number of ΔCO_2 measurements for the space of interest. This is an estimate of the standard uncertainty of ΔCO_2 in the measured space and accounts for the indoor inhomogeneity in CO_2 distribution.

The uncertainty in the measured ventilation rates due to spatial inhomogeneity was again calculated using the approach set out in Section 4.3.1.1. Figure 4.16 shows the ventilation rate results from Flat D against the uncertainties due to sensor uncertainty from the previous section and the uncertainty due to spatial inhomogeneity as described in this section. Table 4.6 shows the mean and standard

Table 4.6: The mean and standard deviations of the uncertainty due to spatial inhomogeneity calculated for ventilation measurements at each of the case study dwellings.

	UTH: Back room	**UTH: Bedroom 2**	**Flat A**	**Flat B**	**Flat C**	**Flat D**
Mean spatial inhomogeneity uncertainty (ach, %)	0.02, 8	0.04, 8	0.10, 12	0.04, 12	0.04, 10	0.04, 11
Standard deviation of spatial inhomogeneity uncertainty (ach, %)	0.01, 6	0.04, 3	0.05, 8	0.05, 13	0.04, 15	0.03, 11
Mean combined uncertainty (ach, %)	0.02, 9	0.05, 9	0.10, 13	0.04, 12	0.04, 11	0.04, 12
Standard deviation of combined uncertainty (ach, %)	0.02, 7	0.04, 3	0.05, 8	0.05, 13	0.04, 15	0.04, 12

deviations of the uncertainties due to spatial inhomogeneity for each case study dwelling. The difference in uncertainties due to each source was more pronounced at CS2, likely because at CS2 measurements related to a whole flat whereas at UTH only a single room was measured and the spatial inhomogeneity in a smaller, less complex, space is likely to be smaller.

The uncertainties from the sensor uncertainty discussed in the previous section and the spatial inhomogeneity were combined in quadrature to give the overall uncertainty which is quoted in the following work. This combined uncertainty is shown in Figure 4.16 and reported in Table 4.6, it can be seen that the uncertainty due to inhomogeneity dominates as the combined uncertainty is close to the inhomogeneity uncertainty.

The opportunity was taken at UTH to explore the effect of mixing fans on the measured ventilation rate results and the uncertainty associated with spatial inhomogeneity, this results of this work are reported in the following section.

4.3.1.3.1 Spatial homogeneity experiments: the use of mixing fans at UTH. Since spatial inhomogeneity is a known issue for tracer gas experiments ASTM (2011) recommends using fans to ensure that air is well-mixed. However, for the measurements at CS2 this was not feasible since the dwellings were occupied. Additionally, Liddament (1996) and others have noted that the use of mixing fans

Table 4.7: The effect of a mixing fan on the uncertainty due to spatial inhomogeneity calculated for the single room measurements of ventilation rate at UTH in which four CO_2 sensors were placed around the room.

Mixing fan status	Mean uncertainty	Standard deviation of uncertainty
Off	$0.02\ h^{-1}$, 8.5%	$0.01\ h^{-1}$, 6.7%
On	$0.008\ h^{-1}$, 2.8%	$0.003\ h^{-1}$, 2.1%

means that the conditions during measurements do not represent conditions during normal occupancy and that this can limit the usefulness of the results. The experiments at UTH aimed to support the interpretation of measurements of ventilation in occupied homes, so the effect of mixing fans on spatial concentration inhomogeneity and ventilation rate uncertainty due to spatial inhomogeneity was investigated.

As described in Section 3.6.1, one of the rooms was instrumented with four CO_2 sensors so that the effect of spatial inhomogeneity could be explored. Mahyuddin and Awbi (2012) found that most researchers consider the middle of an occupied zone and a height of 1.0 m - 1.2 m to be the ideal positioning of a CO_2 sensor in an occupied space; the first sensor was placed in this location. Cui et al. (2015) observed poor mixing close to corners in their experimental work, so the additional sensors in this work were placed slightly away from the corner. One sensor was placed 30 cm from the corner of the room at 1.2 m height; this is likely to represent a typical location of a sensor in an occupied home, where placement on top of cabinets, shelves or stands is convenient for the occupant and likely to be close to walls rather than central. The final sensors were placed at floor level and at a height of 2.0 m in the same location as the second sensor. These final two sensors were placed in non-ideal locations so that spatial inhomogeneity due to stratification was likely.

These experiments were conducted in a single room at UTH focusing on the single room ventilation rate, rather than the whole house. The decay algorithm described above identified 17 periods for ventilation rate analysis when the mixing fan was on. The results include decays prior to and after the external CO_2 sensor was installed but the external CO_2 is not likely to have influenced these results since the focus is on the variability of indoor CO_2 concentration.

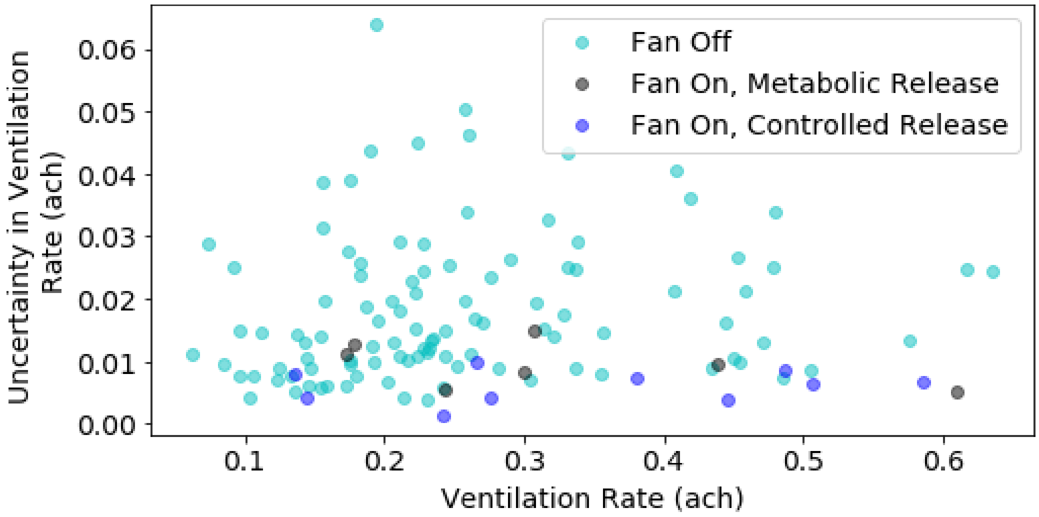


Figure 4.17: Ventilation rates measured the single measurement room at UTH against the uncertainty in these ventilation rates due to the uncertainty associated with spatial inhomogeneity, showing measurements conducted with the mixing fan off (all metabolic CO_2) and mixing fan on.

The uncertainty in the ventilation rates measured at UTH due to spatial inhomogeneity were calculated as described in the section above. Figure 4.17 shows the ventilation rates and calculated uncertainties due to spatial inhomogeneity for measurements conducted with the mixing fan off and on and Table 4.7 gives the mean uncertainties and standard deviation of the uncertainties associated with spatial inhomogeneity for fan on and fan off measurements. As expected, this suggests that imperfect mixing when the fan was off increased the uncertainty associated with the measurement. Even with the fan off the mean uncertainty remains below 10% and given that the measured ventilation rates are usually considerably below 0.5 h^{-1} (often taken as a threshold for adequate ventilation rate) this level of uncertainty does not affect the interpretation that the ventilation rate is too low.

Finally, the ventilation rates were calculated using the individual CO_2 sensors and the deviation from the mean ventilation rate was then used to assess whether there was any systematic effect related to the location of the sensors. Calculations of ventilation rate using the sensor in the middle of the room gave a mean increase of 3.1% in ventilation rate compared to the value calculated using the mean of all four sensors in the room. It is possible that the air moves more freely in the middle of the room than close to the walls and this could account for the difference, or since the source was close to the middle of the room the dispersion of CO_2 could have caused the difference. However, the results are encouraging in the sense that the qualitative interpretation that the ventilation rate is likely too low in this space were not found to be affected by the extent of the spatial inhomogeneity in the space. This study shows that the effect is small in this case study, and while ventilation in every dwelling is different, the impact of placing sensors in more convenient locations for the occupants instead of in the middle of the space is likely to be small.

4.3.2 Unquantifiable uncertainties

The sections above attributed quantities to some aspects of the uncertainty associated with measurement of ventilation rate using the CO_2 decay technique in the manner described in this chapter and using the Eltek GD-47 equipment. However, some of uncertainties related to the measurements of ventilation rate are not quantifiable. This section discusses these uncertainties and their effect on the interpretation of the measured values.

4.3.2.1 Definitional uncertainty and revisiting the measurand

In Section 2.2 different methods for measuring ventilation were discussed and it was argued that these different methods measure slightly different quantities. JCGM (2008) makes clear that uncertainty can arise from incomplete specification of the measurand and from measurement of a quantity which is an approximation of the measurand rather than a quantity fully consistent with the definition of the measurand. Both elements are apparent in ventilation measurements.

Persily (2016) notes that there are several metrics related to ventilation which may be of interest, but that the terminology is not always consistently used. For example, some authors may use ventilation rate to mean the outdoor airflow into a building through intentional openings, whereas others may include unplanned infiltration; in this case the measurand has not been clearly defined. Persily recommends referring to the outdoor ventilation rate when the latter interpretation is intended.

Additionally, different aspects of airflow into a building are of interest depending on the intended use of the measurement. For IAQ studies the distribution and dissipation of pollutants in the space is of interest, whereas for efficiency or heat loss studies the amount of unconditioned air entering a space is the primary concern. This issue can be seen to play a role in the set-up of experiments, for example Liddament (1996) recommends that mixing fans are not used in tracer gas experiments if the aim of the experiment is to learn something about air quality, since areas of poor mixing are of interest in this context. In this case the quantity of interest might not strictly be the amount of outdoor air entering the space, but related to the conditions in the location of an occupant. The measurand and measurement techniques necessary for each kind of study are not the same although the term ventilation rate might be used in all cases.

Persily (2016) notes that the result of a single zone tracer gas decay in a single room (such as the one conducted for single room at UTH) is not the outdoor ventilation rate and it cannot be assumed that this represents the outdoor ventilation rate of the zone nor of the building. This is because flows between the measured space and the rest of the building are not accounted for with this experimental set-up. Persily notes that the measured decay rate may still be of interest, but that care must be taken in its interpretation. The measured value in the single room at UTH is a quantification of how quickly a pollutant decays towards background levels after mixing in a single room and then having the source removed, taking into account the capacity of the building to act as a reservoir of air unpolluted with that contaminant and the dilution of the pollutant due to outdoor air entering the building and polluted air leaving it. This has sometimes been termed an ‘effective ventilation rate’ (Mumovic et al., 2009): i.e. the indoor-outdoor ventilation rate which would be required to produce the observed drop in pollutant if no interzonal flows were present. For the single room measurements at UTH, interpreting the measured decay rate as the outdoor ventilation rate will overestimate the outdoor ventilation rate since adjoining spaces were always lower in CO_2 concentration than the measured room. Therefore the decay rate calculated from the single-room measurements at UTH represents an upper limit to the outdoor ventilation rate in that room.

The interpretation of the measured value differs between the single-room measurements at UTH just described and the whole dwelling measurements at UTH and CS2. In all whole-dwelling experiments CO_2 was distributed around the whole dwelling, by occupants at CS2 and by controlled release at UTH, so the single-zone was interpreted as the whole dwelling. However, neither the dwellings at CS2 nor UTH were detached, so it is possible that there was exchange of air between the measured and adjacent dwellings. This introduces an uncertainty related to interpreting the whole dwelling decay rate as the outdoor ventilation rate. The CO_2 concentration was not measured in the adjacent dwellings at CS2 or UTH (except for in one instance, discussed in the following section), it is therefore not known whether they had lower or higher CO_2 concentrations during decay measurements so there is no clear systematic bias in interpreting the whole-dwelling decay rates as outdoor ventilation rates. At UTH the neighbouring dwelling was also an unoccupied test house and it is unlikely that the CO_2 concentrations were ever significantly elevated, leading to a potential, but unknown, bias towards high ventilation rates. The measured whole-dwelling decay rates can again be interpreted as the effective ventilation rate; the outdoor ventilation rate required to give the observed drop in CO_2 concentration if there were no air exchange with adjacent dwellings.

The measurand in this work is referred to throughout as the ‘ventilation rate’ for brevity, but it is noted that the quantity measured is the ventilation rate required to give the observed decay in CO_2 assuming there is no flow between the measured space and the surrounding building. In general there was no way of knowing the extent of flow between the measured dwellings and their surroundings. However in one case the flow from an adjacent dwelling was clearly identified, the following section discusses this.

4.3.2.2 Flows from adjacent spaces

At CS2, evidence of leakage of CO_2 between flats was observed. Flat B and C were next door to each other and a period in which Flat C was unoccupied coincided with Flat B being occupied, Figure 4.18 shows the ΔCO_2 recorded in each flat during this time. The ΔCO_2 rise in Flat C while it was unoccupied is likely to be due to air flow

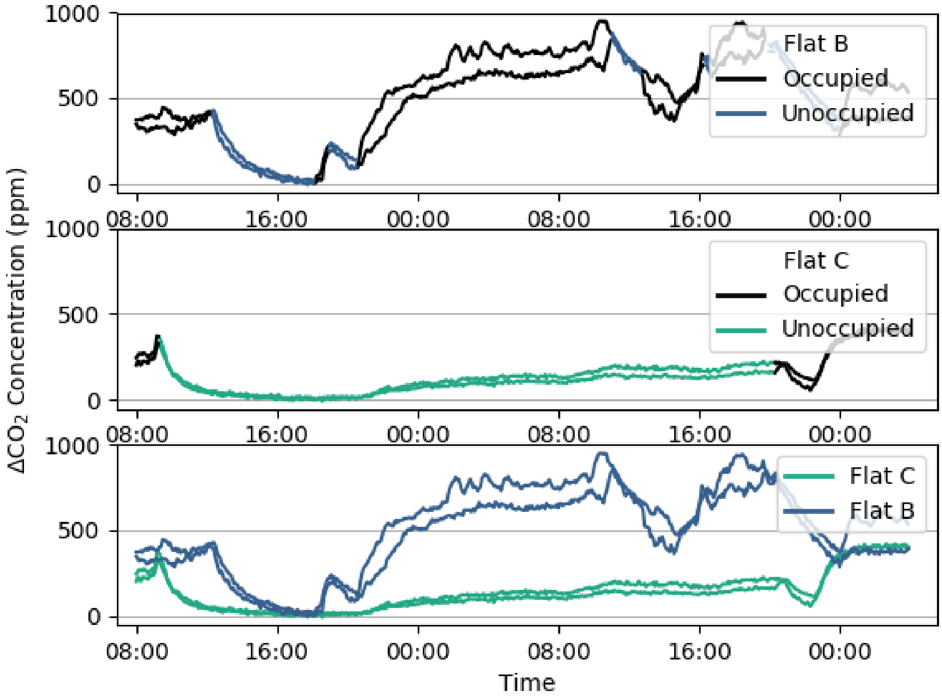


Figure 4.18: A period of ΔCO_2 data for Flat B and Flat C at CS2, these flats were next door to each other and a likely flow of air from Flat B to Flat C is indicated by the rise in CO_2 in Flat C during an unoccupied period. Both flats contained two CO_2 sensors.

from Flat B - the rise starts at the same time as the ΔCO_2 rise in Flat B and has a similar shape but smaller magnitude. This finding shows that flows from adjacent spaces occurred and may have affected the measured ventilation rates. This finding was serendipitous and it is not known how frequently similar events occurred.

Tracer gases which are not naturally present in the atmosphere would similarly be affected by airflows between adjacent dwellings. These would not be observable in the way shown in Figure 4.18, but since the gas would not be present in adjacent dwellings the measured ventilation rate would be known to be a systematic over estimate of the outdoor ventilation rate.

An attempt to estimate the flow rate from Flat B to C was made for the period shown in Figure 4.18, this is presented in the following chapter, Section 5.4.2, in the context of the adequacy of the ventilation at CS2.

4.3.2.3 The effect of ventilation dead-zones

It was noted in Section 2.2.3.1 that the equations relating to tracer gas experiments refer to the 'effective volume' of the measured space. This may not be the same as the physical volume if there are significant 'dead-zones' where air does not mix. The presence of dead-zones introduces uncertainty related to how the conditions vary across the space of interest.

Moreover, assuming the effective volume is the same as the physical volume can introduce systematic effects in the calculation of ventilation rates. The natural units of ventilation rate vary depending on the measurement method. The form of Equation 2.11, the single zone exponential decay of a tracer gas in a space with no source of the gas, means that air changes per hour are naturally calculated in tracer gas decay experiments; whereas the form of the equation associated with constant concentration tracer gas experiments means that volumetric flow units are most naturally calculated. Conversion between the air changes per hour and a volumetric flow rate requires the estimation of the 'effective volume' of the ventilated space. Estimating the effective volume is not straightforward, Sherman (1990) suggest the effective volume is rarely known to better than 20%. Air changes per hour are usually quoted here since this is the natural unit for tracer gas decay experiments. When the air changes per hour results are converted to a volumetric flow (for example to compare to the rates quoted in ADF) the geometric volume of the measured space is used in this work, this will give an overestimate of the effective volume which results in a systematic shift towards larger volumetric flow rates. The effect of this overestimate of volumetric flow rate would be to indicate a higher heat loss than realistic, while the disparity between the IAQ indicated by this volumetric flow rate and the IAQ the occupant experiences would depend on the occupant's location relative to any dead-zones.

4.3.2.4 Uncertainties associated with the occupancy algorithm and analysis algorithm

The occupancy algorithm and analysis algorithm together identified periods of decaying ΔCO_2 from which to calculate the ventilation rate. The limitations of these were discussed in Sections 4.1 and 4.2.3 respectively. Such limitations and the possibility that inappropriate periods of data were analysed contribute to the unquantifiable uncertainty associated with the measurement. As described in the sections above, steps were taken to reduce the likelihood of such events, but especially at CS2 where the conditions were not controlled this remains an unquantifiable possibility.

4.4 Development of ventilation measurement method summary

Through Chapter 2, it was shown that the ventilation measurement techniques applied in homes are often not developed to facilitate the measurement of long-term variability in ventilation rates. In particular, PFT methods have frequently been used to give an average ventilation rate over a period of days, weeks or months and other methods have often been used to give a small number of 'snap-shot' measurements. This can mean that it is challenging to understand how the ventilation rate changes over the range of conditions that occupants are likely to experience. The work presented in this chapter sought to develop the analysis of monitored data from extended campaigns to facilitate repeated CO_2 decay ventilation rate measurements and to understand the limitations and uncertainties in the approach developed, thereby supporting the long-term measurements of ventilation rates in occupied homes. This was achieved through three main components: development of the occupancy status algorithm (OSA), development of the decay identification and analysis algorithm, and a detailed investigation of the quantifiable and unquantifiable uncertainties associated with the measurement.

It was noted in Section 3.2.3 that previous examples of tracer gas experiments using metabolic CO_2 used simple methods for identifying periods of data with appropriate occupancy, often relying on occupant records, assumed occupant schedules or manual identification. While these methods may be appropriate for short monitoring campaigns, for this research it was necessary to develop a robust, reliable and repeatable method for identifying periods when the studied dwellings were unoccupied to reduce the researcher burden associated with application of the ventilation rate measurement method. The OSA was tested in an occupied flat (OAF), the occupants recorded when OAF became occupied and unoccupied, the occupancy status determined by the OSA agreed with the occupant records in 87% of cases. The version of OSA tested in OAF used CO_2 concentration data, event-monitored front door opening data and state-monitored internal door opening data. Detailed investigation of the instances where the OSA incorrectly classified the occupancy status according to the occupant records suggested that window use and frequent internal door use prevented the OSA from correctly classifying the occupancy status of the dwelling. Subsequent deployments of the OSA at CS2 therefore included event monitoring of internal doors and windows, this is likely to have improved the performance of the OSA significantly. The CO_2 decay technique requires that there are no sources of CO_2 present during the measurement. The OSA allowed the unoccupied periods of the monitored data to be quickly and reliably identified, this unoccupied subset could then be passed to the decay identification and analysis algorithm with high confidence that any decays identified in that subset took place in the absence of occupants.

Similar to the OSA, the decay identification and analysis algorithm reduces the researcher-time burden associated with identifying appropriate periods of ΔCO_2 decay data for ventilation rate analysis, it facilitates robust and reliable identification of such periods. The development of this algorithm explored the effect of parameters such as the amount of smoothing, minimum and maximum decay time and minimum ΔCO_2 threshold on the measured ventilation rates and number of identified decays. It was particularly striking to note that the difference in ventilation rates calculated using an assumed constant background CO_2 concentration was up to 0.8 ach at UTH compared to using continuously measured external CO_2 concentration. A threshold limit in the amount of external CO_2 variation allowed during decays and in the preceding hour was applied since variation in the external concentration effectively violates the assumption that the only change in concentration is due to the exchange of indoor air with the assumed infinite reservoir of constant concentration outdoor air. This threshold limit caused between 4% and 46% of decays at the different case studies to be rejected. This effect is little discussed in the literature, but this scale of rejected measurements and the potential magnitude of the error introduced are both significant. The application of such thresholds by the decay identification and analysis algorithm help to ensure that the resulting measurements are robust.

The final part of this work explored the uncertainties associated with the measured ventilation rates in detail, including quantifiable and unquantifiable effects. These unquantifiable aspects include definitional uncertainty, flows between adjacent spaces, the effect of dead-zones and the uncertainties associated with the possibility of incorrect classification of unoccupied periods or decay periods by the algorithms developed for this work. Many of these uncertainties are shared by other ventilation measurement methods, for example all single zone analyses taking place in non-detached buildings will have an uncertainty related to the flows between adjacent spaces. This uncertainty can be negated either by conducting a multi-zonal analysis using multiple tracer gases or measuring a whole detached building. Similarly, without sampling a tracer gas at many points in the measured space it is not possible to reduce the uncertainty associated with imperfect mixing or the possibility of ventilation dead-zones to zero. Of the quantifiable uncertainties, the most significant element was the spatial inhomogeneity of CO_2 in the measured room or dwelling. At UTH this resulted in a mean uncertainty of 3.4% of the measured value for the single room measurements. At CS2 the mean uncertainty due to spatial inhomogeneity ranged between 10% and 12% of the measured value between the four flats.

Taken together, the algorithms developed in this chapter combine to facilitate long-term measurements of the variability of ventilation rates in occupied homes. These can help to reduce reliance on ‘snap-shot’ measurements of ventilation in dwellings or on PFT methods which average ventilation rates over days, weeks or months. Combined with a long-term monitoring campaign this means that the variability of ventilation over time: the effect of wind, temperature differences and occupant actions on ventilation rates can be explored in occupied homes. Coupling the application of these algorithms with monitoring of doors and windows means that measurements taken with different configurations can be disaggregated and their effect on ventilation rates can be explored. The following chapter presents the results from UTH and CS2 where such effects were investigated.

Chapter 5

Variation in Ventilation and Adequacy of Ventilation

The literature review in Chapter 2 showed that ventilation rates in occupied dwellings are likely to be variable due to weather and occupant actions. The ventilation measurement method presented in the previous chapter explored how the CO_2 decay method could be developed to address some of the concerns highlighted in the literature review regarding the feasibility of long-term, temporally disaggregated ventilation measurements in occupied homes. The performance and uncertainty of the developed method were investigated in a number of case study dwellings. The current chapter presents the results of the ventilation measurements using the method developed in the previous chapter; these results are used to explore the variability of ventilation in the case study buildings investigated and gain deeper insights into how the ventilation rates experienced by occupants vary over time.

The ventilation measurements were carried out in an unoccupied test house (UTH) and four occupied homes at CS2. The measurements at UTH had two purposes: firstly to test the method and secondly to explore the variability of ventilation rates due to changing weather conditions and due to the effect of common occupant actions. UTH was built in the 1930's and does not comply with recent ventilation regulations, nonetheless this dwelling is typical of a significant proportion of the UK dwelling stock (see Section 3.6.1). The dwellings at CS2 were converted from an office block in 2015 and were designed to comply with the continuous MEV system in ADF. The method developed in the previous chapter was used in an extended monitoring campaign at CS2, this presented an opportunity to assess the extent to which the method could give insights regarding the ventilation rates actually experienced by the occupants over time. The measurements at CS2 also allowed insights into the extent to which these dwellings, which were required to meet the ventilation regulations at the time that they were converted to dwellings in 2015, delivered adequate ventilation as-occupied given variations in weather conditions and occupant actions.

The results from UTH are presented in the first half of the chapter in Sections 5.1, 5.2 and 5.3. The results of experiments at UTH investigating the effect of closure of trickle vents, doors and curtains are presented first. Insights from these results are limited by the changing weather conditions affecting ventilation rates during measurements so Section 5.2 develops models of the influence of temperature difference and wind on the results so that the results from different configurations can more robustly be compared. Section 5.3 then discusses the adequacy of the ventilation at UTH and the implications of the findings from this case study. The second half of the chapter, Sections 5.4 and 5.5, deals with the results from the occupied dwellings at CS2. The implementation in occupied dwellings of the OSA and analysis algorithms developed in the previous chapter is presented first including the limitations of the method as-applied. The variation in ventilation is then discussed in Section 5.5 with reference to the occupants' use of windows and doors, weather conditions and the differences between occupied and unoccupied periods. Finally, the conclusions and implications drawn from both sets of case studies are discussed in Section 5.6.

5.1 UTH: ventilation rates in different configurations

This section presents the results and interpretation of the ventilation rates measured at UTH under different configurations. Unoccupied periods of data were identified using the OSA, although only the front door, back door and doors to the single measurement rooms were monitored. This helped to test the OSA since most of the occupied times were known to the author (although sometimes site security or other researchers entered the building). The ventilation rates were analysed using the analysis algorithm as described in the previous chapter. Several different experimental configurations were investigated, these were chosen to investigate a number of possible occupant actions which have been associated with ventilation rates in previous literature (discussed in Section 2.4). The base case against which different configurations were compared for the single room measurements was trickle vents open throughout the dwelling, door of the measurement room closed and all other doors open, metabolic CO_2 release without mixing fans and curtains open, Section 3.6.1.3 discussed the experimental set-up at UTH in more detail. The experiments are summarised below.

Trickle vents are intended to ensure that buildings are adequately ventilated: they are a component in three of the four ADF approved systems for ventilation, and are recommended in existing buildings when windows are replaced (HMG, 2013b). As discussed in Section 2.4, despite the prevalence of trickle vents there are limited studies on their performance. Low ventilation rates have been observed in naturally ventilated dwellings with trickle vents (Crump et al., 2005; Sharpe et al., 2014) and many occupants keep them closed (Sharpe et al., 2015). The trickle vents were closed and all other configurations remained the same as the base-case for the first set of experiments. Most of these measurements took place in the back room at UTH, with some in bedroom 2 (see Figure 3.2).

Little research has addressed the difference in ventilation rate measured on different spatial scales or with internal doors closed. Bekö et al. (2010) and Sharpe et al. (2015) measured only bedrooms, while Oreszczyn et al. (2005) and Keig et al. (2016) all characterised only the whole house ventilation rate, Johnston and Stafford (2017) compared the n/20 rule to the ventilation rate in two rooms, but did not discuss the different spatial scales of the measurement. The base-case and single room with trickle vents closed case was compared against two whole house measurements; one each with trickle vents open and closed.

It has been suggested that the use of curtains at night in bedrooms could obstruct the flow of air from trickle vents, reducing the ventilation rate in a space which is already likely to have reduced ventilation due to closed doors (Sharpe et al., 2014). Experiments with curtains closed in the measurement room and all other conditions as the base-case were taken. The final configuration had all internal doors closed, all trickle vents closed except those in the measurement room and all other configurations as for the base-case. All these experiments took place in the back room.

Table 5.1 gives the number of measurements recorded for each configuration investigated. Many more measurements were taken in the base-case condition as the rest of the results were compared to this so it was necessary that these experiments took place with weather conditions similar to those during all other experimental configurations.

5.1.1 Trickle vents open and closed in a single room at UTH

A series of trickle vents open and closed measurements were taken at UTH to investigate the effect of trickle vent use. The measurements took place between September and December 2018 for the back room, and between January and February 2019 for bedroom 2. Measurements were taken with trickle vents closed in bedroom 2, but after excluding measurements for which the external CO_2 was unstable only two trickle vents closed results remained. As a result, only the eight remaining trickle vents open results are presented for bedroom 2. Table 5.1 shows the weather conditions and number of measurements for each configuration.

Figure 5.1 presents a histogram showing the measured ventilation rate results with trickle vents opened and closed in the back room. Closed trickle vents are clearly associated with significantly lower ventilation rates, although almost all measurements with trickle vents open also fall below the recommended ventilation rate of 0.5 ach. There is a significant spread in the ventilation rates in both cases, likely due to the variable weather conditions during the measurements. Section 5.2 explores the variation in these results with the weather conditions and Section 5.3 discusses the implications of these findings.

Table 5.1: Number of measurements and indication of weather conditions during the measurement of ventilation rates under different configurations. The mean, maximum and minimum temperature differences (indoor - outdoor) and wind speeds are shown respectively, and the median wind direction is given.

Configuration	**Measurements**	**Temperature difference (°C)**	**Wind speed (Knots)**	**Wind direction (°)**
Back room. Trickle vents open.	62	6, 15, -3	6, 14, 1	243
Back room. Trickle vents closed.	39	5, 11, -3	6, 12, 1	257
Back room. Curtains closed	9	9, 19, 8	7, 10, 4	234
Back room. Whole house closed.	11	11, 13, 8	7, 12, 3	225
Bedroom 2. Trickle vents open.	8	16, 22, 8	4, 10, 1	254
Whole house. Trickle vents open	1	12	5	204
Whole house. Trickle vents closed	1	14	8	240

5.1.2 Whole-house and single-room ventilation rates at UTH

Two whole house tests were carried out in February 2019: one with trickle vents open, the other with trickle vents closed. The results are given in Table 5.2, along with a summary of the single-room trickle vent open and closed results for comparison. The weather conditions during these tests are given in Table 5.1

The method and analysis for the whole-house experiments was slightly different to the single-room experiments at UTH. CO_2 concentration was raised using controlled release from a gas cannister in all rooms, which meant it was necessary to use fans to encourage mixing throughout the dwelling, and all internal doors were open throughout the experiment. Despite the use of mixing fans, the homogeneity

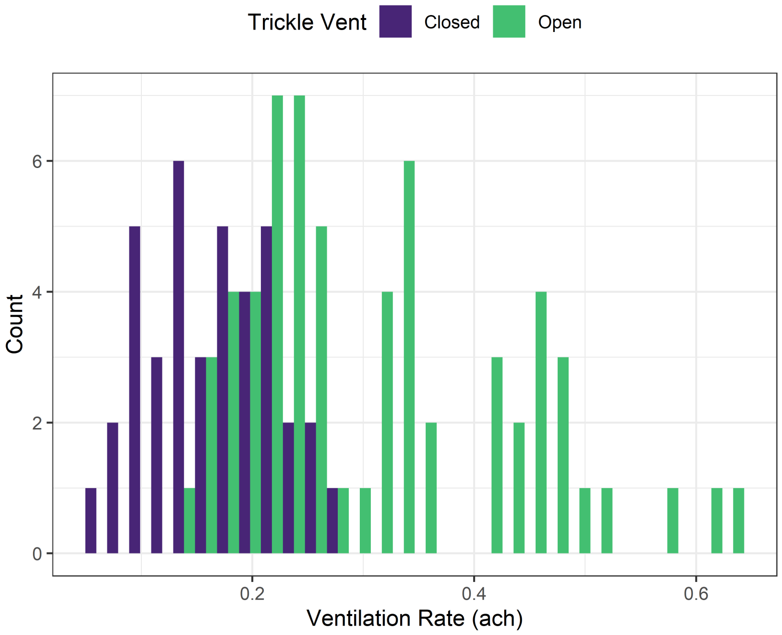


Figure 5.1: Histogram of the single-room ventilation rates measured at UTH in the back room with trickle vents open and closed.

Table 5.2: Summary of measurement results characterising the whole house and single rooms with trickle vents open and closed. The standard deviation is given in brackets after the mean results for the back room and bedroom 2, the uncertainty in whole house ventilation rate measurement as described in the text is shown in brackets after the whole house measurement results.

Measurement	**Trickle Vents Open**	**Trickle Vents Closed**
Air Permeability	-	15.1 m^3 /hr /m^2
ACH_{50}	-	15.1 ach
$N_{50}/20$	-	0.8 ach
Whole house CO_2 decay	0.8 ach (0.1 ach)	0.7 ach (0.2 ach)
Mean back room CO_2 decay (standard deviation)	0.3 ach (0.1 ach)	0.2 ach (0.1 ach)
Bedroom 2 CO_2 decay	0.5 ach (0.2 ach)	-

threshold used in the rest of the analysis (10% or 40 ppm as discussed in Section 4.2.2) was not maintained during the whole house experiments. The ΔCO_2 concentrations recorded downstairs remained within 10% of each other, as did the upstairs concentrations. There were differences of up to 30% in ΔCO_2 concentrations between upstairs and downstairs. Three of the CO_2 sensors were located in bedroom 2 during these experiments so using the simple mean of the ΔCO_2 concentration would have erroneously weighted the results towards the concentration in this room. As a result, the volume-weighted average ΔCO_2 concentration was calculated and used in place of the mean ΔCO_2 concentration in the analysis of these results. These issues demonstrate how the spread of pollutants around a building is complicated, and characterising ventilation with a single value does not necessarily reflect this complexity.

The uncertainty attributed to the whole house results (see Table 5.2) relates to the different ventilation rates calculated using upstairs and downstairs sensors due to imperfect mixing in the dwelling. The upstairs ΔCO_2 concentrations are systematically biased towards higher values because CO_2 flows from downstairs to upstairs due to buoyancy effects, therefore the ventilation rate calculated using upstairs ΔCO_2 concentrations is systematically biased towards lower values. Analysis of the upstairs ΔCO_2 concentration gave a decay constant of 0.7 ach for trickle vents open and 0.5 ach for trickle vents closed. The uncertainty on the whole-dwelling ventilation rate given in Table 5.2 is the difference between the result found using all sensors and using only the upstairs sensors, this uncertainty is likely to dominate the uncertainty in the measured value and this estimation gives a conservative estimate of the uncertainty. Since the ventilation rates calculated using the upstairs ΔCO_2 concentration are at or above the common threshold of 0.5 ach, this does not contradict the interpretation that the whole dwelling is over-ventilated despite the inability to maintain uniform concentration.

The whole house ventilation rate was above the threshold of 0.5 ach with trickle vents open and closed, and the dwelling is therefore well ventilated from an IAQ perspective, but likely to be inefficient to heat. In contrast, the back room single room ventilation rate is below 0.5 ach with trickle vents open and closed. The results from bedroom 2 are less reliable because there are fewer results, but the mean is 0.5 ach and five of the eight measurements were below 0.5 ach. Taken together these results suggest that despite a whole dwelling ventilation rate that indicates adequate ventilation, individual rooms could have issues with poor IAQ when their door is closed. This is discussed further in Section 5.3.

5.1.3 Closure of all trickle vents and internal doors

Single room measurements in the back room were taken with all internal doors closed and all trickle vents closed except those in the measurement room in January 2019. The weather conditions and number of measurements are shown in Table 5.1. The mean ventilation rate was 0.4 ach (standard deviation = 0.1 ach). This value similar is to the base-case 0.3 ach (standard deviation = 0.1 ach) measured in the back room with doors and trickle vents in the rest of the house open. However, the impact of closing the internal doors throughout the UTH is not clear given the confounding weather variations. Analysis of the impact of the weather conditions is presented in Section 5.2, allowing further investigation of this issue.

5.1.4 Curtains open and closed

The base case conditions in the back room were also compared to measurements taken with the curtains in the back room closed. The mean ventilation rate with curtains closed was 0.4 ach (standard deviation = 0.1 ach). Again, this value is similar to the base-case result in this room 0.3 (standard deviation = 0.1 ach). These curtains were floor length but slightly set away from the wall and the windows were recessed into the wall, see Figure 5.2. It is likely that different kinds of curtains would interact with the flow of air in different ways, but this was not investigated further. Again the weather conditions will influence the results and this is explored further in Section 5.2.

5.1.5 Summary of different configurations at UTH

The different configurations tested at UTH showed that some common actions potentially have a significant effect on the ventilation rates experienced by occupants.

(a) Closed curtain

(b) Open curtain

Figure 5.2: Photographs of open and closed curtains in the back room at UTH.

A significant difference was observed between the ventilation rate in a room with the door closed compared to the whole-dwelling ventilation rate. The status of the trickle vents was also seen to have a small impact on the ventilation rate in the back room, although this was not enough to raise the single-room ventilation rate to adequate levels. This is despite the tested room having more trickle vent area than required by ADF and the tested dwelling being exceptionally leaky compared to modern standards. Closure of curtains and closure of other internal doors and trickle vents had little effect on the measured single-room ventilation rate.

All the results presented so far in this section must be interpreted with caution since the experiments took place under different weather conditions and variation in ventilation rate is expected since the ventilation driving forces varied during different measurements. This makes comparison of the results in different configurations difficult to interpret since differences could be caused by changes in driving forces rather than the changes in the configuration of the dwelling. The following section discusses the effect of temperature difference and wind on the results so that the implications of the variation in ventilation rate due to different configurations can be discussed in Section 5.3.

5.2 Ventilation rate and natural driving forces at UTH

The theory of ventilation in terms of pressure differences caused by fans, wind and temperature difference between indoors and outdoors were discussed in Section 2.1. Naturally ventilated spaces, such as UTH, experience different ventilation rates depending on the indoor temperature and weather conditions, this is the case for all real homes (except those dominated by mechanical ventilation). The results presented above require further investigation because the weather conditions were variable for each measurement. Therefore, the following work sets out to explore the relationship between wind and temperature difference on the ventilation rates measured in UTH, and their subsequent impact on the ventilation rates resulting from specific occupant practices discussed in the previous section.

Section 5.2.2 presents the forms of models of ventilation based on temperature difference and wind found in the literature and discusses the models fitted to the data collected from UTH, the performance of these models is then discussed in Section 5.2.3. Finally, Section 5.2.4 uses the results of the weather models to give insights into the effect on ventilation rate of the different configurations presented in the previous section. Firstly, the treatment of the weather data for the purpose of this investigation is briefly presented in the following section.

5.2.1 Weather data

The wind data from a nearby weather station was downloaded from the MIDAS database (Met Office, 2019) and the external temperature was measured outside

UTH, as described in Section 3.6.1. In order to analyse the effect of the weather on the ventilation rate results, the weather data was averaged over the period of each decay experiment. The arithmetic mean of the external temperature and temperature in the measurement room were used to calculate the mean temperature difference during the decay. Following Burt (2012), the scalar average of wind speed was calculated and the vector average of the wind direction was calculated. There was no correlation between the external temperature, wind speed or wind direction. The MIDAS data was reported hourly but decay experiments did not always align exactly with this data. The data used to average the wind speed and direction over the decay experiments was weighted according to the amount of time for which the MIDAS data point overlapped with the decay experiment.

5.2.2 Models of ventilation driving forces at UTH

The physical mechanism of ventilation is driven by pressure differences between indoors and outdoors, as presented in Section 2.1. The relationship between pressure difference and flow rate is given by:

$$Q = c(\Delta p)^n, \tag{5.1}$$

where Q is the airflow rate, c is the flow coefficient, Δp is the pressure difference across the opening and n is the flow exponent. The flow exponent n, varies between 0.5 for fully turbulent flow and 1 for fully laminar flow. Whilst the exact flow exponent depends on a wide range of factors, flow is generally taken to be turbulent through large openings such as windows and laminar through very small holes in a building fabric (ATTMA, 2016).

Pressure differences arise from temperature differences and wind in a naturally ventilated building such as UTH. Considering these effects separately, the temperature difference is linearly related to the pressure difference, while the pressure difference due to wind is proportional to the square of the wind speed. Assuming that the pressure differences from temperature difference and wind can be simply added then a relationship of the following form would be expected for the total pressure difference:

$$\Delta p = A\Delta T + Bu^2, \tag{5.2}$$

where ΔT is the temperature difference and u is the wind speed. The theory of the relationship of pressure difference with temperature difference and with wind were discussed in Section 2.1.1 along with the coefficients A and B.

Recently, authors such as Pan et al. (2019) and Caciolo et al. (2011) have explored the influence of wind and temperature on single-sided ventilation through open windows in experimental studies. These studies have predicted ventilation rates with known opening areas (or at least known dominant openings) and with the assumption of turbulent flow and a flow exponent of 0.5. These studies found that the best performing models were of the form:

$$Q^2 = C\Delta T + Du^2, \tag{5.3}$$

where C and D are coefficients. This is the expected relationship for a flow exponent of 0.5 and a simple addition of pressure differences per Equations 5.1 and 5.2.

However, there are relatively few recent empirical studies of the effect of wind and temperature difference on ventilation rates in domestic buildings without windows open, and most available studies took place in the 1960's and 70's (Persily, 2016). However, Wallace et al. (2002) reviewed this literature and found different kinds of relationships were reported: some where only temperature difference was significant, others only wind speed. Some found a linear dependence with both temperature difference and wind speed; others found square root relationships with temperature; others found a squared relationship with wind speed. Where wind and temperature were both taken into account, some found that the relationship was additive, while others found subadditive relationships. As discussed in the theory of ventilation Section (2.1), wind direction will affect the wind surface pressure coefficient and therefore the effect of wind on ventilation rate. However, wind direction was usually not considered in the literature reviewed by Wallace et al. (2002) or Persily (2016). Nonetheless Malik (1978) found a significant relationship between the measured ventilation rate and $u.cos(\theta+\gamma)$ where u is the wind speed, θ is the wind direction and γ is an angle which was varied to maximise the goodness of fit of the model. Malik (1978) found that γ varied between the angle of orientation of the tested building and 20 degrees from the orientation depending on the wind speed. This means that the term $u.cos(\theta+\gamma)$ relates to the wind incident on the tested building.

Since the evidence from the experimental literature did not clearly favour any particular model, several models were tested on the back room ventilation rate results from UTH. The models tested are presented in Table 5.3. Models were fitted which combined temperature difference and wind speed raised to the powers of 0.5, 1 and 2 since there were examples from previous literature of each of these powers best describing measurement data. Models with linear temperature difference dependence and quadratic wind speed dependence (models 1, 6, 11 and 15) are therefore physically expected to perform best if the pressure differences caused by temperature difference and wind speed can be simply summed.

Models were also fitted with the flow exponent varied between 0.5 and 1. Table 5.3 shows results for a flow exponent of 1 for clarity, the ventilation rates were low so it was expected that the cracks in the fabric were reasonably small and therefore that the flow was largely laminar. The results were very similar and trends in the best performing model were the same regardless of the flow exponent.

Multiple linear regression models were applied to the single-room ventilation rates measured in the back room at UTH using an ordinary least squares fitting algorithm (statsmodels module in Python (Seabold and Perktold, 2010)). Separate models were fitted for the results with trickle vents open (N=62) and with trickle vents closed (N=39) data. Table 5.3 shows the models tested and the goodness of fit as described by the adjusted R^2 number, Akaike information criterion (AIC) and the root mean square error (RMSE). All models were fitted with a constant term, even though without temperature difference or wind there would be no pressure difference to drive ventilation. Eisenhauer (2003) raises several issues related to regression through the origin. Firstly, suppressing the intercept excludes the possi-

Table 5.3: Goodness of fit parameters for the fitted models of the single room ventilation rate measured at UTH with the trickle vents open and closed. All models were fitted with coefficients for each term, not shown in the table, and a constant term.

Independent variable(s)	**Open**			**Closed**		
	Adjusted R^2	AIC	RMSE	Adjusted R^2	AIC	RMSE
1. $\Delta T + C$	0.06	-86.8	0.116	0.24	-123	0.048
2. $\sqrt{\lvert\Delta T\rvert} + C$	0.05	-86.1	0.117	0.25	-124	0.047
3. $\Delta T^2 + C$	0.08	-88.2	0.115	0.27	-124	0.047
4. $u + C$	0.05	-86.0	0.117	0.23	-122	0.048
5. $\sqrt{u} + C$	0.03	-84.3	0.119	0.23	-122	0.048
6. $u^2 + C$	0.09	-88.9	0.114	0.19	-120	0.049
7. $\theta + C$	0.40	-115	0.093	-0.02	-112	0.055
8. $\cos(\theta + \gamma) + C$	0.45	-120	0.089	0.13	-117	0.051
9. $\Delta T + u + C$	0.29	-103	0.100	0.62	-149	0.033
10. $\sqrt{\lvert\Delta T\rvert} + u + C$	0.27	-101	0.102	0.60	-147	0.034
11. $\Delta T + u^2 + C$	0.33	-107	0.098	0.56	-143	0.036
12. $\Delta T + u + \cos(\theta + \gamma) + C$	0.65	-146	0.070	0.70	-157	0.029
13. $\Delta T + u + u.\cos(\theta + \gamma) + C$	0.69	-152	0.066	0.75	-164	0.027
14. $\sqrt{\lvert\Delta T\rvert} + u + u\cos(\theta + \gamma) + C$	0.67	-149	0.068	0.71	-159	0.028
15. $\Delta T + u^2 + u.\cos(\theta + \gamma) + C$	0.72	-160	0.062	0.75	-163	0.026

bility for discontinuities in the response of the dependent variable, also regression through the origin may result in non-zero mean residuals since a line through the origin is generally inconsistent with the best fit. In the present case it is also possible that temperature differences may exist between rooms even if the temperature difference between the measurement room and outdoors was zero.

Models 1 to 6 are single variable models of ventilation with temperature difference and wind speed. Models 9 to 11 combine temperature difference and wind speed. All these models show clear differences between the trickle vents open and closed results. None of the single variable models have strong explanatory power, but the models using the trickle vents closed data perform much better than those using trickle vents open data. The combined temperature difference and wind speed models (9 to 11) also perform better for models using trickle vents closed data. Of these models, the simple physical expectation of linear temperature difference and quadratic wind speed (model 11) performed best for trickle vents open data, but worst for trickle vents closed.

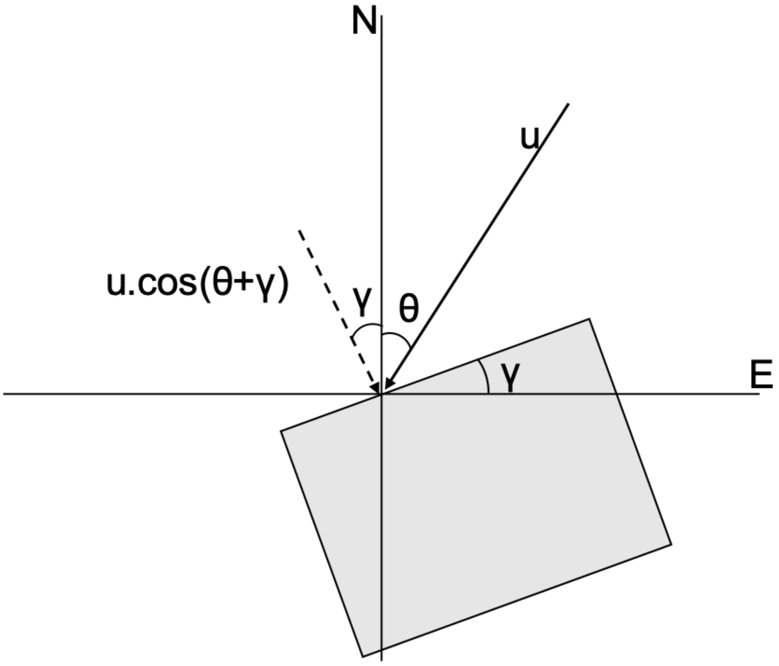


Figure 5.3: Schematic diagram showing the orientation of the exposed façade of the single measurement room at UTH. The parameter u.cos($\theta + \gamma$) physically represents the component of the wind vector, *u*, perpendicular to the exposed façade of the single measurement room at UTH.

Models including wind direction were also tested using the $cos(\theta + \gamma)$ relationship as proposed by Malik (1978). The value of γ was varied and the value for which the model performed best was used in the subsequent analysis, for models using trickle vents open or closed data, $\gamma = 19^\circ$ performed best. Physically the term $u.cos(\theta + \gamma)$ is the component of the wind speed normal to the exposed façade of the measured room as shown in Figure 5.3, this result is similar to the findings of Malik (1978). The results of models 7 and 8 in Table 5.3 show that wind direction has almost no explanatory power for models using trickle vents closed data but much more for the trickle vents open.

For both trickle vents open and closed the best performing models combine all three parameters (models 12 to 15). The adjusted R^2 and AIC values attempt to account for the increase in goodness of fit associated with adding any variable by penalising more complex models so this is not likely to be due to over-fitting the models. For models using trickle vents open or closed data model 15 performs best, this model uses the expected relationship from a simple addition of the pressure differences from wind speed and temperature difference with the addition of the wind speed component normal to the exposed façade of the measured room. There is very little difference between model 15 and 13 when using trickle vents closed data.

In order to further assess the best-performing model, a validation set approach was used. In this method, the observations are randomly divided into a training set and a validation (or hold-out) set (James et al., 2017); the training set is then used to fit the model. This fitted model is then used to predict the responses for the data in the validation set and the RMSE can then be used to assess how well the model is able to predict the results of unseen data (James et al., 2017). A random sample 20% of the data points (N=8 for trickle vents closed and N=12 for trickle vents open) were held back for the validation set and this process was repeated 10 times using new divisions of training and validation sets. The mean RMSE of the holdback dataset was 0.034 for the trickle vents closed and 0.062 for the trickle vents open data. These results are very similar to the RMSE when all data was used (as in Table 5.3) and this indicates that the model describes the observed data well.

5.2.3 Discussion of driving forces models

In the section above, models of the effect of ventilation driving forces on the ventilation rate were fitted to the single room ventilation rate results for trickle vents open and closed and were shown to describe the variation in ventilation rates well. The form of the best fitting model for the results above was different to many of the results in the previous literature and is unusual in that the wind direction was found to be an important variable (Wallace et al., 2002).

Sinden (1978) considered the effect of temperature difference and wind on pressure differences across a building envelope theoretically, he conducted a number of thought experiments which help to explain why different relationships may be found by many different authors. Sinden (1978) considers how the locations of the cracks or openings in the building envelope can affect the way temperature or wind influence the pressure difference across the envelope and the consequent ventilation rate. Sinden considers scenarios in which an increase in wind speed first decreases the ventilation rate compared to ventilation driven by temperature difference alone, but a further increase in wind speed over a critical value causes the ventilation rate to increase. In this scenario the relationship between wind speed and ventilation rate is not monotonic - this was rarely considered in the examples from the literature and was not explored in this thesis. This scenario and others in his paper show how the wind direction and location of cracks in the building fabric are crucial factors in the form of the relationship between changes in temperature differences and wind speeds on ventilation rates.

Many studies have shown, using pressurisation tests and smoke surveys, that cracks and openings are not uniformly distributed in real buildings. However, there is no method currently available which can satisfactorily characterise the location, sizes and flow characteristics of cracks in the building envelope. This means that, apart from the intended ventilation pathways, it can be challenging to model flow paths in a real building. The present case, UTH, is a particularly leaky dwelling, so the locations of the unplanned leakage pathways may be particularly important compared to the planned ventilation openings. It is common that cracks or openings in the façade are assumed to be uniformly distributed when modelling ventilation rates, such as in the modelling software DOMVENT (Lowe, 2000) and DOMVENT3D (Jones et al., 2014). Other modelling software such as CONTAM allows specification of individual flow paths and their characteristics (Dols and Walton, 2002). Some research details specific flow path locations, for example Nabinger and Persily (2008), Shrubsole et al. (2014), and Cardoso et al. (2020), but it is common that research using such models do not report how airflow paths have been modelled, for example Dovjak et al. (2020) and Argyropoulos et al. (2020).

The results presented suggest that as expected the response of a building to ventilation driving forces can depend on the configuration of small openings such as trickle vents. Since the best performing model was different when trickle vents were open or closed the resulting ventilation response has not simply taken the form of increased effective area (which would simply increase the value of the coefficients, not change the best model). Building up a greater base of measured performance of

Table 5.4: Mean bias and root mean square error (RMSE) of the single room ventilation results measured in different configurations compared to the ventilation rate expected using the model of the effect of wind and temperature difference on trickle vents open ventilation rate. The closed house configuration refers to all internal doors being closed and all trickle vents except those in the measurement room.

Configuration	Mean bias (ach)	RMSE (ach)
Trickle vents open	-	0.06
Trickle vents closed	-0.14	0.15
Closed house	-0.01	0.10
Closed curtains	0.08	0.15

buildings with various construction types, extent of retrofit and planned ventilation would help to give further insights into variability of ventilation with wind speed, direction and temperature. However, it has been shown that the location of cracks in the fabric are likely to influence the response of a building to temperature and wind. We do not have adequate methods for characterising these cracks and cannot extrapolate that the model which best describes the UTH results would also describe the ventilation in another building well. The form of the best fitting model in this case is similar to Malik (1978), but not to the findings of other authors.

The best performing models described the variation of ventilation rate with wind and temperature difference well for the single room ventilation rates at UTH. This meant it was possible to assess whether the different configurations in which ventilation was measured resulted in measurably different ventilation rates. These findings are presented next.

5.2.4 Difference in ventilation rate with different configurations

The models identified in the previous section were used to clarify the results of the ventilation experiments at UTH. The results from different configurations were compared to the results expected using the model fitted with the trickle vents open data from the back room at UTH. The mean bias and root mean square error are shown in Table 5.4, and the measured results are plotted against the modelled results in Figure 5.4.

The results of different configurations in the back room can now be more ro-

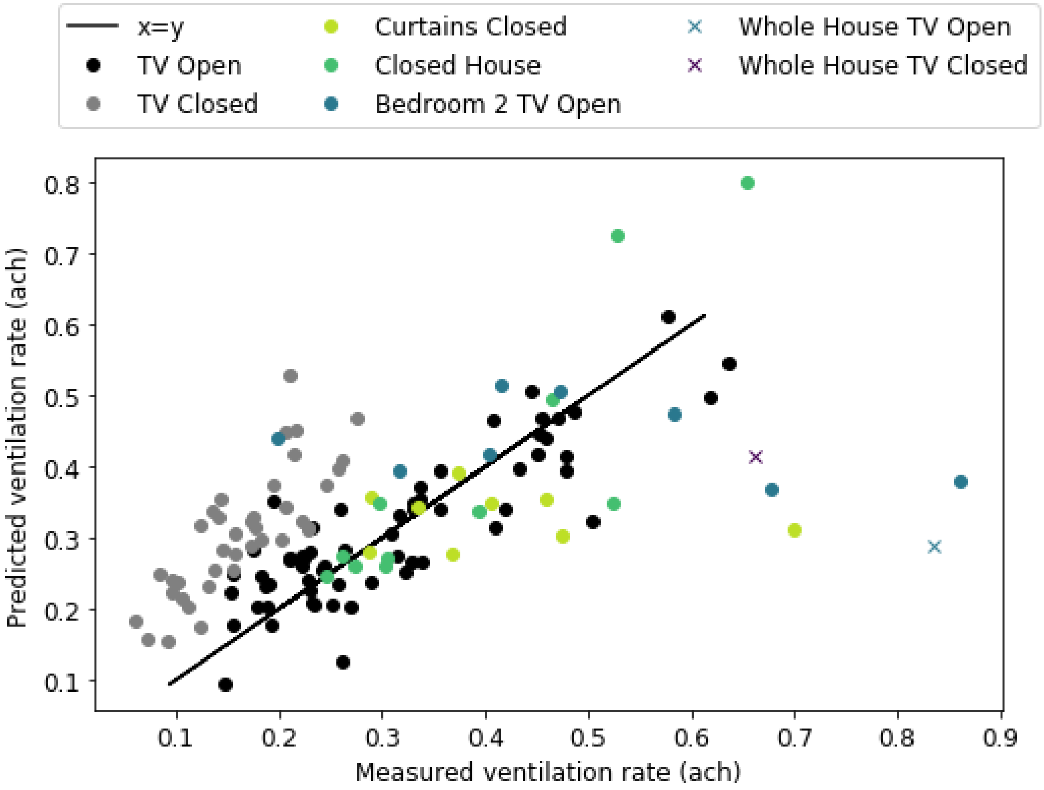


Figure 5.4: Ventilation rates measured in the single measurement room at UTH in various configurations against the ventilation rate predicted by the trickle vents (TV) open model of effect of temperature difference and wind on ventilation rate.

bustly compared. Firstly, the mean bias result shows that the trickle vents closed configuration results in lower ventilation rates than trickle vents open, as expected. The closed house configuration (all internal doors closed and all trickle vents closed except those in the measurement room) is not systematically different to the trickle vents open model; the mean bias is very small so the data points are fairly evenly distributed around the predicted ventilation rates and the RMSE is fairly similar to the trickle vents open data. Therefore, the doors and trickle vents other than those in back room do not appear to have a significant effect on the ventilation rate in the back room. The curtains closed data is slightly biased towards higher ventilation rates than expected by the model. However, there is no obvious physical mechanism by which closing curtains would result in higher ventilation rates, and Figure 5.4 shows that one particularly high ventilation rate was recorded in the curtains closed configuration, this may be an anomalous result. Further curtains closed data would be necessary to draw firm conclusions.

Figure 5.4 shows that the whole house ventilation rates are not well predicted by the back room model. The difference between the ventilation rate predicted by the back room trickle vents open model and the measured whole house trickle vents open result was 0.54 ach, and for the trickle vents closed model and whole house trickle vents closed result was 0.25 ach. This shows that there is a significant difference between these results, indicating that the whole house ventilation rate is not a good indicator of the conditions in an individual room.

The following section discusses the implications of the findings from UTH.

5.3 Insights from the results at UTH and informing the study at CS2

There are several important implications of the results from UTH related to the impact of arranging the dwelling in different configurations. The implications are discussed with reference to policy and further research after the limitations of the findings are discussed.

5.3.1 Limitations

As with all methods to estimate ventilation rates, several limitations apply to this study. In particular, results from this case study may not be generalised to the wider stock. However, this building is of typical construction for a house built during the 1930s in England, and the available evidence suggests that the dwelling has typical characteristics: the airtightness is typical of older stock (Perera and Parkins, 1992) and similar leakage paths locations have been found in other dwellings (Stephen, 2000). This study therefore identifies issues that are likely to occur more widely in the stock, with unknown prevalence and highlights issues of relevance to policy and practice that may form the basis of further study.

The single zone approximation was used for the single room measurements, neglecting flow between rooms. The implications of this were discussed in Section 4.3.2. In this case the CO_2 concentration in adjacent rooms was measured and was always below the concentration in the measurement room during decay periods used for analysis, so any airflow to other internal spaces will have systematically biased the result towards higher values. The true indoor-outdoor ventilation rate is therefore likely lower, this means the resulting heat loss will be lower but the impact of any interzonal flow on IAQ depends on the pollutant sources present in other rooms.

Whole house tests were conducted once, whereas multiple tests were conducted in the single room; further whole house experiments would have been desirable. The influence of weather on whole house ventilation rates could not be explored, but the weather conditions during the whole house tests were not atypical (as shown in Table 5.1). The results suggest that single room results were significantly different to the whole house results.

5.3.2 Effect of dwelling configuration on ventilation rates

The results show that measurements of ventilation on different spatial scales can differ significantly. The whole dwelling value suggests that the dwelling is over-ventilated, while the single room with door closed measurements suggest a ventilation rate that may not be high enough to ensure good IAQ in typical room use over a wide range of temperature difference and wind conditions. The exposure of occupants to pollutants depends on how long they spend in a specific room, whether they close internal doors, the ventilation rate and pollutant sources. For example: the use of candles, cleaning products, drying of clothes or simply the presence of several people are all events that could take place in a room with the door closed and could lead to poor IAQ (Satish et al., 2012; Porteous et al., 2014; Dimitroulopoulou et al., 2015).

To date there has been relatively little empirical work exploring how internal spaces are divided and used by occupants. Banfill et al. (2012) found that particular doors were opened and closed at regular times each day, while particular rooms were almost permanently closed off due to adult children moving away. McDermott et al. (2010) found several reasons people opened or closed doors including: watching children in next door rooms, letting light in, and blocking sounds. Sharpe

Figure 5.5: Photograph from a smoke survey while UTH was pressurised, showing an air leakage pathway behind the kitchen cupboards.

et al. (2015) found that bedroom doors were often closed overnight and doors were more likely to be open when a child is present.

The difference in whole house and single room ventilation rates is likely to be caused by a range of factors, including the non-uniformity of air leakage paths and limited air exchange between spaces with closed doors. The dwelling is leaky compared to modern properties, but is fairly typical of older dwellings (Perera and Parkins, 1992). A qualitative smoke pen investigation revealed several significant air leakage paths in the under stairs cupboard, around the services in the kitchen and bathroom, through several cracks in the walls and around the front door. The windows were well sealed. Figure 5.5 shows an example of the smoke being drawn into the space behind the kitchen cupboard, while the house is pressurised by blower door. Between-room air flow may be encouraged by door undercuts; ADF requires undercuts of 7600 mm^2 in new buildings. However, the measured room had undercuts approximately half this size, which will have significantly reduced the airflow to the rest of the building. This may explain why changes affecting the ventilation rate in other parts of the house, closing internal doors and trickle vents, had no significant effect on ventilation rate measured in the back room.

The trickle vents in this dwelling were unable to raise the single room ventilation rate to an adequate level. Further work is required to determine if this issue is widespread, but this result is in line with previous authors (Crump et al., 2005;

Sharpe et al., 2015). Whilst increasing the number or size of trickle vents would improve the ventilation rate with the internal door closed, it would contribute to increased excess ventilation with the door open. The problem of low ventilation rates is exacerbated by the findings of several authors that trickle vents are frequently closed in occupied dwellings (Crump et al., 2005; Sharpe et al., 2015), despite the stated intention in ADF that they are permanently open. The role of occupant practices on ventilation rate is significant and measures designed to provide adequate ventilation must account for their actions.

The results of the ventilation models showed that wind direction was a much more important explanatory variable for the trickle vents open case compared to when they are closed. No other studies empirically reporting on the effect of trickle vent use on the relative importance of different driving forces to ventilation rates have been identified in the extensive literature review in Chapter 2. Future research comparing the results of theoretical ventilation models to this empirical finding would be of interest to investigate whether such effects can be accurately predicted.

This research found no clear evidence that closure of curtains in the measurement room or closure of trickle vents and doors in the rest of the dwelling affected ventilation rates in the measured room. The style and coverage of curtains might be expected to affect the air flow paths and therefore the ventilation rates, as well as the depths of door undercuts. Since only one property has been studied here, and the impact of curtains on ventilation rates in other rooms has not been studied, further research into the impact of curtains and blinds on ventilation rates would be informative, particularly because trickle vents are often located in window frames and are therefore likely to be covered by curtains.

Since trickle vents are an important part of several common ventilation systems, as outlined in ADF, the findings relating to the use of trickle vents combined with door use have some important potential implications for policies relating to ventilation in dwellings, as discussed in the following section.

5.3.3 Implications for policy

At present, ADF specifies ventilation strategies for new buildings which are assumed to meet the requirements for adequate ventilation. These provisions differ depending on the planned air permeability of the building. However, the results presented above show that whole dwelling ventilation rates are not necessarily representative of the conditions in different parts of the dwelling. Moreover, the distribution of air leakage pathways is generally not known, so infiltration through unplanned leakage pathways does not necessarily provide ventilation in the spaces that it is needed or guarantee good IAQ.

ADF recommends, but does not require, that trickle vents are installed when windows are replaced in existing buildings. However, the installation of replacement UPVC glazing units is likely to increase the airtightness of a room and may result in reduced IAQ (Oreszczyn et al., 2005). The trickle vents improved the ventilation in the single room at UTH where replacement UPVC windows had been installed (though were unable to raise it to adequate levels). These results highlight that, whilst the background ventilation in this room was not able to reach to recommended 0.5 ach, inclusion of background ventilation is important after works that are likely to significantly affect the ventilation rate. Requiring such provision in all rooms when changes are made that could influence the air change rate in a space could help to mitigate associated IAQ issues.

This research has highlighted that the current building regulations are not designed to take into account differences between the performance of the whole building compared to individual rooms. Two measures that may address the observed disparity for naturally ventilated buildings are the use of undercuts for doors and vents between rooms. Undercuts with an area of 7600 mm^2 are required by ADF for new buildings and may improve flow between rooms with closed doors. However, there are no requirements for undercuts for existing buildings, except where a new wet room is added. Whilst the magnitude and scale of this issue is not known, requiring either undercuts or between room vents when doors are replaced, or when major building work is completed on a property, could improve the single room ventilation rate without increasing the whole building ventilation rate with internal doors open.

Potential occupant acceptability issues arise for undercuts or vents: they allow cool draughts which may decrease thermal comfort, and they allow noise and smells to travel between rooms. ADJ recommends noise attenuating vents when they are installed to provide adequate combustion air for flued appliances (HMG, 2013c), and similar vents may provide a partial solution.

Additionally, in considering how to improve airflow through dwellings the need for buildings to be fire-safe must be considered. Fire doors are tested for fire safety compliance with a particular undercut, up to a maximum of 25 mm (BSI, 2008). Any adjustment to the undercuts would require re-testing doors for their fire safety with a new undercut depth. Similarly, in order to comply with Approved Document B (HMG, 2013a), vents between rooms should not be used in fire-resisting walls and vents should be placed at low level to reduce the spread of smoke, this prevents placement of vents at high level to improve thermal comfort.

Mechanical ventilation could help alleviate issues related to the distribution of ventilation around dwellings. Although, in a dwelling with air permeability as high as UTH (in common with much of the British stock), mechanical ventilation would not be energy efficient on the whole building scale (Lowe, 2000). This highlights the challenge of balancing IAQ and energy efficiency concerns in occupied dwellings.

UTH had been retrofitted with double glazing, but the above issues are likely to become increasingly important in the coming years as existing dwellings undergo extensive energy efficiency retrofits in order to meet climate change mitigation goals. Such interventions are likely to affect the airtightness of buildings (Symonds et al., 2019) and the flow of air throughout. Ventilation is known to be a challenge in the context of retrofit, and the guidance in BSI (2019) highlights that ventilation should be considered from the early stages. This recognises the building as a system of connected elements in which the occupants' practices and lifestyle must be taken into account. The results above indicate that occupant use of doors and trickle vents are likely to influence the ventilation rates they experience, and this may be an important factor to consider in providing adequate ventilation in dwellings as-occupied after retrofit. Chapter 6 explores occupant use of ventilation equipment in more detail.

The manifestation of ventilation in occupied buildings requires further research given that the way occupants use a building is influential yet challenging to account for when designing adequate, robust and safe guidance and regulations for ventilation. The research at CS2 further investigated ventilation in occupied homes and the following section outlines how the results of the work at UTH influenced the research at CS2.

5.3.4 Implications for this research

The findings at UTH supported and guided the investigation of ventilation at CS2 in several ways. Firstly, the UTH findings suggested that further work on how spaces and doors within buildings are used would support a better appreciation of the conditions that occupants experience, and their relation to whole house ventilation rates, or rates in specific rooms. It was therefore important to monitor internal doors as well as windows at CS2. Unlike UTH, the CS2 dwellings were occupied so the conditions within were not controlled and gathering such relevant data to help interpret the results was important. Finding that the use of doors can be highly relevant to the ventilation rates in a space also supported the inclusion of doors as a relevant technology in the qualitative data collection.

The issues related to trickle vents identified at UTH and in the literature informed the decision to study occupied dwellings with this technology. Additionally, the research at UTH highlights the importance of understanding occupant practices in CS2, since actions such as trickle vent and door opening may have a significant impact on ventilation rates. The study at CS2 therefore undertook a long-term detailed monitoring campaign including door use in dwellings with trickle vents aiming to explore how their use (or not) affects ventilation in occupied homes.

5.4 Measuring ventilation at CS2

The flats at CS2 were monitored between June 2019 and January 2020, the data collected over this period were analysed using the occupancy and ventilation rate analysis algorithms described in the previous chapter. The external sensor was required for calculation of ΔCO_2 for ventilation rate analysis, this was installed in July 2019 as described in Section 3.6.3. Figure 5.6 shows an example of 3 days of ΔCO_2 data, window and door opening data from Flat C; the figure shows that the algorithms are able to identify CO_2 decays for ventilation measurement. 29, 141, 194 and 169 ventilation rate measurements were recorded for Flat A, B, C and D respectively.

Although many ventilation measurements were recorded, in applying the measurement method in occupied dwellings several issues arose which affected the interpretation of the results. These are detailed in the following sections, including discussion of the relatively small number of results from Flat A. The presentation of the measurement results and analysis of the variation of ventilation rates measured follows in Section 5.5.

5.4.1 Flat A: frequently open windows and low CO_2 concentrations

The number of decays identified for Flat A was much lower than for the other flats at CS2. Unlike Flats B and C, Flat A was not a studio so CO_2 was dispersed over a larger volume. Additionally, one of the occupants at Flat A frequently worked from home meaning that the dwelling was less often unoccupied than the other flats. Also, windows were often open at Flat A, especially when the dwelling was unoccupied. As a result, CO_2 concentrations in this flat were generally low and the homogeneity criteria described in Section 4.2.2 were rarely met when the dwelling was unoccupied. Figure 5.7 illustrates the generally low CO_2 concentrations during unoccupied times and spread in CO_2 concentrations on some occasions when the dwelling is unoccupied.

It is also possible that the placement of the CO_2 sensor in the bedroom was

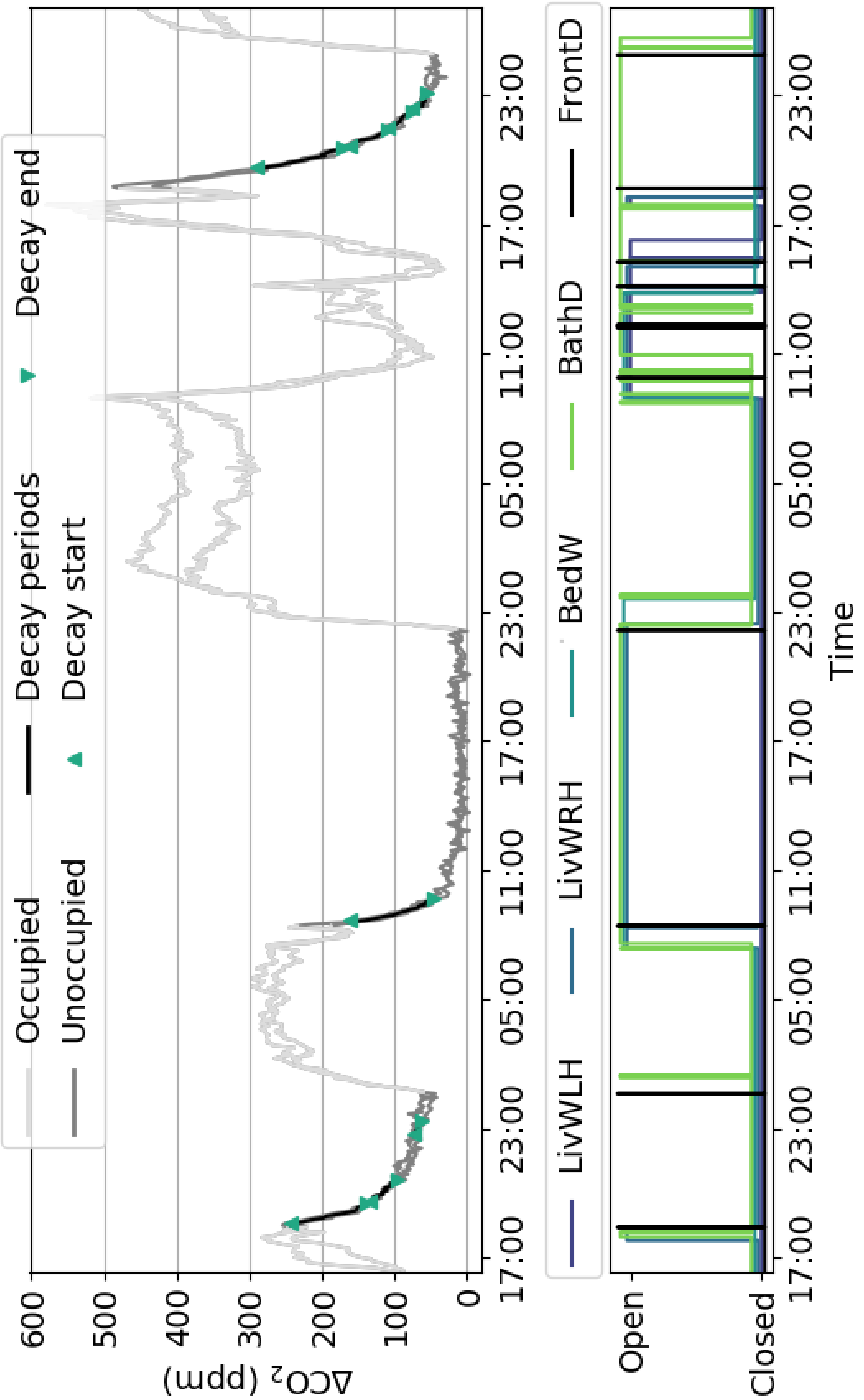


Figure 5.6: Example two day period of data from Flat C at CS2. The top figure shows the ΔCO_2 data with periods identified as occupied and unoccupied, and periods used for ventilation measurement also highlighted. The bottom figure shows the door and window opening data for the same period. The legend for the doors and windows uses the following abbreviations: Liv = living room, Bed = bedroom, Bath = bathroom, W = window, LH = left hand, RH = right hand, D = door.

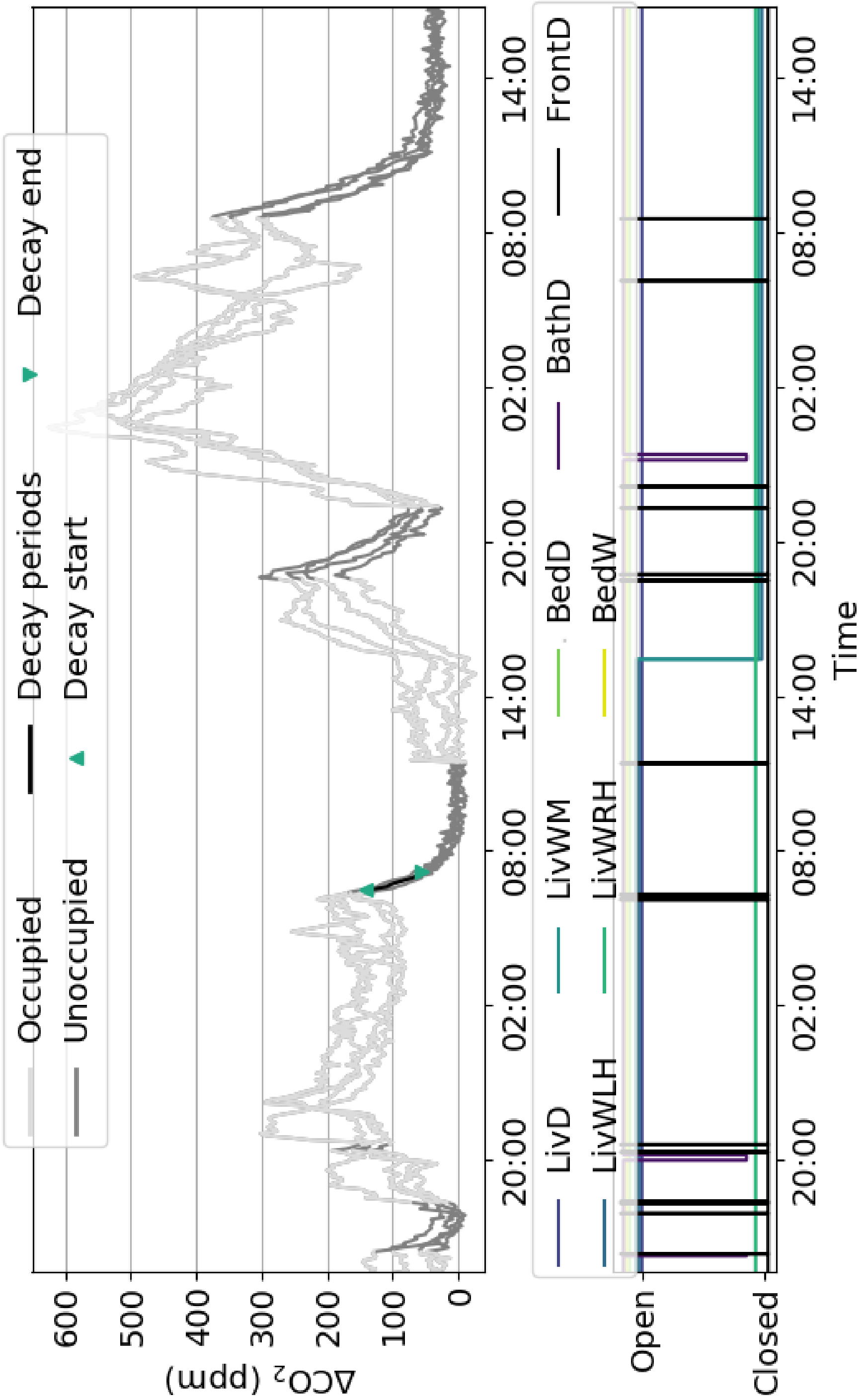


Figure 5.7: Example two day period of data from Flat A at CS2. The top figure shows the ΔCO_2 data with periods identified as occupied and unoccupied shown, and periods used for ventilation measurement also highlighted. The bottom figure shows the door and window opening data for the same period.

too close to the window, biasing the CO_2 measurement toward low values when the window was open. This sensor placement was chosen because of the availability of electricity supply in the room, highlighting one of the challenges of undertaking research in real homes. This could also explain why no decays were recorded when only the bedroom window was open even though this configuration accounted for over 20% of the unoccupied periods. However, removing the bedroom sensor from the analysis did not increase the number of decays identified so this is not thought to be the dominant factor leading to the small number of decays identified in the dwelling.

When the same homogeneity requirements were applied in Flat A as for the rest of the case studies only three decays were identified across the entire monitoring period. This was too few to meaningfully interpret the results. The uncertainty calculation described in Section 4.3.1.3 explicitly accounts for the spread in CO_2 concentrations across the dwelling to calculate the uncertainty in the ventilation rate measurement due to spatial inhomogeneity. Therefore it was decided to relax the homogeneity requirement for Flat A and accept a higher uncertainty associated with the results from Flat A. The homogeneity threshold was increased by 10 ppm to 50 ppm or 10% of the measured ΔCO_2 concentration. This increased the number of identified decays to 29. Over 100 decays were identified in all other flats so flat A still recorded far fewer results, but this is sufficient to give an indication of the conditions in Flat A.

The issues experienced in analysing this flat point to an inherent limitation of the ventilation measurement method used: the extent to which the findings reflect the ventilation conditions in the home and the uncertainty of the results depend on the ways that the occupants live in their homes. Although these issues limit the quantitative analysis of ventilation rates in some homes, they do support qualitative investigation. The low CO_2 concentrations in Flat A indicate that there were likely few issues related to indoor sources of pollution in this dwelling but heat loss is likely to have been high in the winter. By relaxing the analysis criteria for Flat A, some results have been obtained which indicate the ventilation rate in several

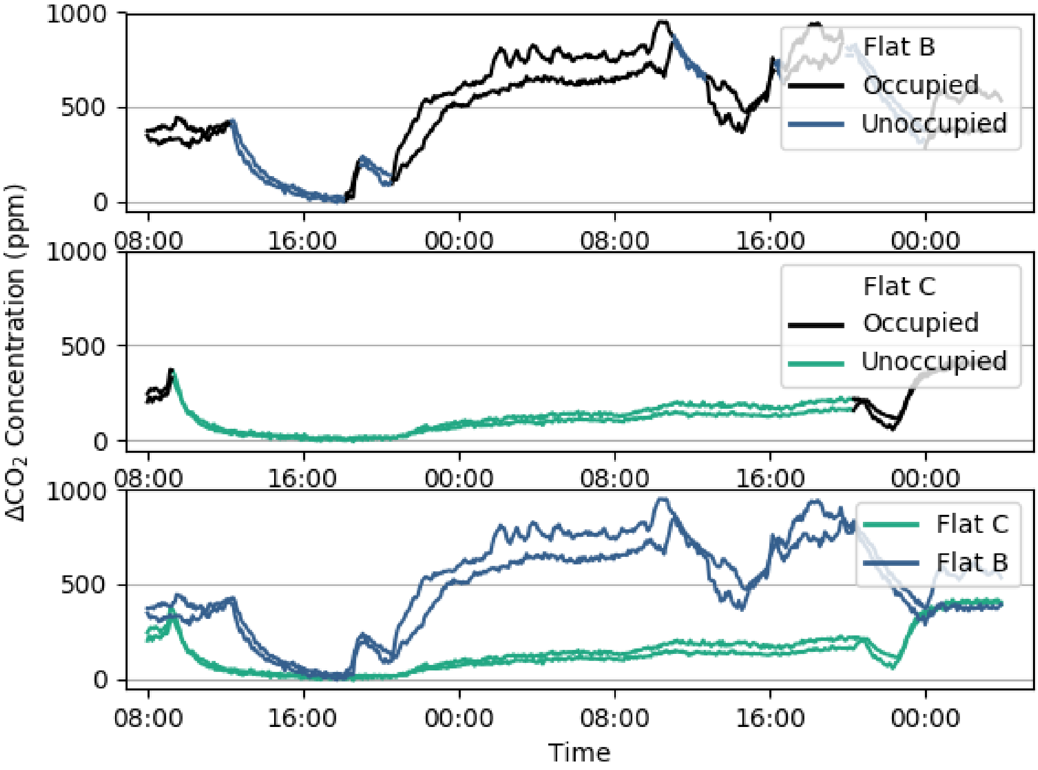


Figure 5.8: A period of ΔCO_2 data for Flat B and Flat C at CS2, these flats were next door to each other and a flow of air from Flat B to Flat C is indicated by the rise in CO_2 in Flat C during an unoccupied period.

configurations. The inclusion of such properties enables useful insights into the use of windows and combined with the qualitative research in the following chapter, Flat A provides insights into ventilation in occupied homes.

5.4.2 Flows between flats

As discussed in Section 4.3.2, evidence of air leaking between Flats B and C was observed. Figure 5.8 shows a rise of ΔCO_2 in Flat B caused by the occupants and a corresponding rise in Flat C during which time Flat C was unoccupied.

The flow rate from Flat B to C during this period was estimated. The approximately constant values of ΔCO_2 in both flats at 6 am were then used to estimate the inter-flat flow rate. The effective CO_2 generation rate due to the flow from Flat B to C was calculated using the equilibrium equation presented in Section 2.2.3, for this

Table 5.5: Estimates of flow rate between Flats B and C and required pressure differences for different gap sizes

Flat C ventilation rate	**Q_{BC} (l/s)**	**Pressure for flow through gap 6x150 mm (Pa)**	**Pressure for flow through 3 gaps 6x150 mm (Pa)**
Closest measurement to leakage period	3.5	49	5.4
As above, if all 4 adjacent flats contributed equally	0.4	0.6	0.1
Maximum ventilation rate with same configuration	4.5	80	9
Median ventilation rate with same configuration	1.4	7.8	1

case the generation rate was:

$$G = Q_{outdoor,C} \Delta CO_{2eq,C}, \tag{5.4}$$

where G is the generation rate of pure CO_2 required to maintain the observed equilibrium concentration of CO_2 in Flat C, $Q_{outdoor,C}$ is the volumetric outdoor ventilation rate in Flat C, and $\Delta CO_{2eq,C}$ is the equilibrium ΔCO_2 in Flat C.

The rate of air leakage from Flat B to C was calculated using G. The concentration of ΔCO_2 in the air flowing from flat B to C is assumed to be equal to the mean ΔCO_2 concentration measured in Flat B during this period. The flow rate can then be calculated simply by considering the volume of air rather than generation of pure ΔCO_2 as follows:

$$Q_{BC} = \frac{G}{\Delta CO_{2,eqB}} 10^6, \tag{5.5}$$

where Q_{BC} is the volumetric flow rate of air between Flat B and C and $\Delta CO_{2eq,B}$ is the equilibrium ΔCO_2 concentration in Flat B.

Several different plausible estimates for the parameters in the above calculation were used to give a range of possible values for Q_{BC}, these are given in Table

5.5. The ventilation rate for Flat C was estimated in three different ways. Firstly the mean of the two ventilation rates measured during the decay from approximately 9 am to 12 pm on the first day shown in Figure 5.8 (0.9 ach) was assumed to represent the ventilation rate throughout the whole period. Converting this to a volumetric rate by assuming the whole volume of Flat C took part in the ventilation gave 21 l/s. Additional calculations were made using the median and maximum ventilation rates measured in Flat C over the entire measurement campaign with the same configuration of windows as observed at this time. Additionally, it is possible that other neighbouring flats contributed to the rise of CO_2 in Flat C; an estimation is given for the limiting case that four neighbouring flats equally contribute to raising the concentration in Flat C. These results give an indication of the possible flow rates but further research, for example using a co-pressurisation test, would be necessary to firmly characterise the flow rate.

Understanding the range of potential characteristics of this flow between the flats is important for several reasons. Firstly, this finding potentially raises an important point related to the fire safety of the dwellings since in the event of a fire in Flat B it is plausible that smoke could leak into Flat C. Given this concern analysis was carried out regarding whether this finding suggested that the flats did not meet current fire regulations. According to Approved Document B (ADB) (HMG, 2010a) which gives guidance related to fire safety regulations, flats should be separated by 'compartment walls and floors' and these should form a complete barrier between the compartments they separate. The findings here suggest that there is a leakage pathway between two flats. ADB further states that compartment walls should not fail BSI 476 for at least 60 minutes. The relevant criteria of BSI 476 is failed if a '6 mm diameter gap gauge can penetrate a through gap such that the end of the gauge projects into the furnace and the gauge can be moved in the gap for a distance of at least 150 mm' (BSI, 2014, p. 9). Thus whether the wall meets the requirement of being a compartment wall depends upon the size and shape of the leakage path between the flats.

Unfortunately it was not possible to assess the nature of the flow path between

Flats B and C. However, as an indication of the feasible total size of the leakage pathways between the flats, the required pressure differences between Flats B and C were calculated for each estimated Q_{BC} assuming a gap of 6mm x 150mm, these are shown in Table 5.5. The results of this simple analysis show that for the higher potential flow rates between Flats B and C it is infeasible that the total area of the flow path is as small as 6mm x 150mm; pressure differences between flats of approaching 50 Pa are not realistic. If a greater total area of flow path is assumed then the pressure differences become more reasonable. However it was not possible to know whether the nature of the flow path between the flats was one large gap, which would automatically fail the requirements of BSI 476, or several smaller gaps, which would not.

Air flows between flats also raises the possibility that pollutants present in one flat may spread to adjacent dwellings. This would mean that poor indoor air quality in one dwelling could affect adjacent dwellings. The extent of any implications of this would depend on the specific pollutant present, its concentration and the amount of air flowing between the dwellings. Further work is necessary to assess the prevalence of air leakage between flats and the implications of such scenarios for fire safety and spread of pollution.

Finally, this finding has implications for the measurement of ventilation rates using CO_2 decays. If such leakage of CO_2 occurs during ventilation rate measurements then the results would be influenced by the input of additional CO_2 from adjacent flats. Such a scenario was discussed in Section 4.3.2.2; depending on the concentration of CO_2 in the adjacent spaces this could bias the ventilation rate result to higher or lower values. The case of Flats B and C just discussed was very unusual in that both dwellings were being monitored simultaneously; in general it was not possible to know whether adjacent spaces had higher or lower CO_2 concentrations. The extent of the influence on ventilation rate measurements is not known. However, it is possible that this effect was worse at Flat C because Flat B's ventilation system was switched off, leading to the continuous extract ventilation in Flat C drawing in more air through this ventilation path than would be observed if both flats had operational units. This highlights one of the potential issues with MEV: it is necessary that air barriers to spaces not intended to contribute to ventilation are effective since air will be drawn in through all available flow paths. CO_2 rises during unoccupied periods as high as that shown in Figure 5.8 were not seen in the rest of the data collected at CS2.

As discussed in Section 4.3.2, the reported ventilation rates are the effective ventilation rates: the outdoor ventilation rate required to reduce the ΔCO_2 concentration as observed assuming no leakage to other indoor locations.

5.4.3 Applying the measurement method to occupied dwellings: discussion

This section discussed the application of the measurement method discussed in Chapters 3 and 4 to occupied dwellings and the key limitations that arose in doing this. The key issues discussed, spatially inhomogeneous tracer gas concentrations and leakage between flats, would likely affect other tracer gas techniques as well. This highlights a key challenge of measuring ventilation in buildings with multiple dwellings without the ability to control the conditions in the studied and adjacent spaces. However, the use of CO_2 as a tracer gas did enable investigation into air leakage between flats, an issue related to the integrity of the studied dwelling, and this method could identify (but could not quantify) such issues in other studies with no adjacent CO_2 data.

Techniques using controlled release of tracer gases may not suffer to such a degree from occupant use of windows since a greater concentration of tracer gas could be released, although achieving spatial homogeneity would remain a challenge. The current method is limited by the amount of metabolic CO_2 generated by the occupants and sometimes this places limitations on the results. Additionally, the CO_2 decay method requires that the space is unoccupied during measurement, non-CO_2 based methods could measure during occupied times and thus more easily capture configurations not seen during unoccupied times.

Despite these limitations to the study, the measurement method was applied to collect a large number of ventilation rates under different configurations and conditions, delivering a range of insights. The following section presents the results gathered at CS2, with reference to the adequacy of ventilation, the variation in ventilation rates measured and the different configurations of doors and windows in which the occupants arranged their homes.

5.5 Variation of ventilation at CS2

Over 100 ventilation measurements were recorded for each of Flats B, C and D; as already discussed far fewer were recorded for Flat A. The ventilation rate results were categorised according to the configuration of doors and windows during the decay period; and the variation of ventilation over time and with different configurations of doors and windows was analysed. Figure 5.9 shows the ventilation rates measured for each flat split by configuration, with results presented for every configuration in which there were more than 15 measurements. The figure shows that there are considerable differences between the dwellings, both in the ventilation rates measured and the configurations of doors and windows in which measurements were taken. Tables of the ventilation rates, their uncertainties, and weather conditions and configurations of doors and windows during the measurement time are given in Appendix D

This section discusses the variation of ventilation rates measured, first with reference to the different configurations of doors and windows. Ventilation rates during occupied times are of interest since these will influence the exposure to pollution that the occupants experience, particularly as related to pollutants released while the occupants are present (for example cooking or cleaning related pollutants), as well as the temperature experienced by the occupants. Clearly ventilation during unoccupied periods is also important for pollutant exposure (since this impacts the concentration of pollutants built-up during unoccupied periods) and heat flows. The method applied during this research requires dwellings to be unoccupied, so how these represent the configurations and likely ventilation rates during occupied periods is an important consideration. Sections 5.5.2 and 5.5.3 explore the extent to which the measured ventilation rates can be used to give insights into conditions

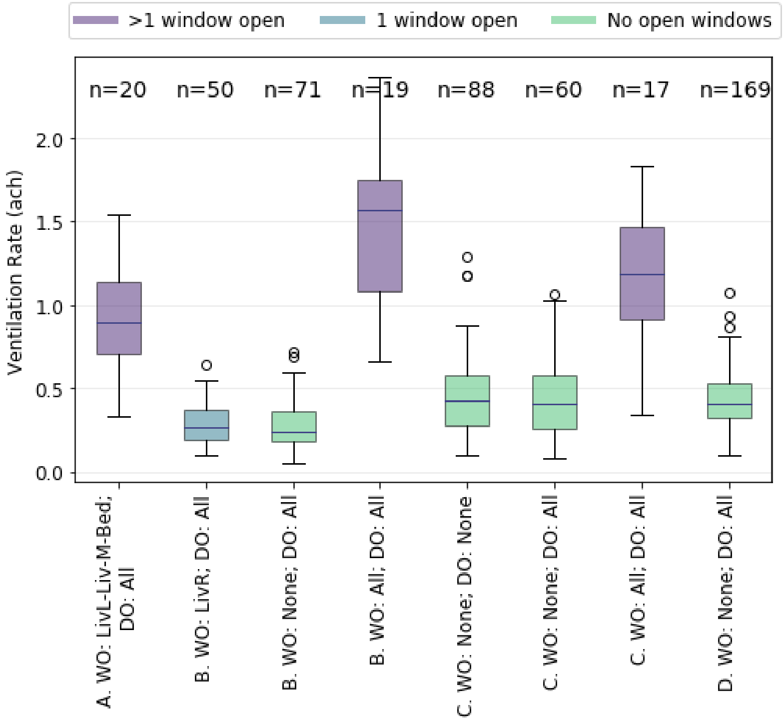


Figure 5.9: Box plots of ventilation rates for each configuration of doors and windows with more than 15 measurements at CS2. The midline indicates the median, the boxes extend between the first and third quartile, the whiskers extend beyond the boxes to a maximum of 1.5 times the interquartile range, measurements outside this range are shown as outliers. The number of observations is indicated. WO = windows open, DO = doors open, Liv = living room, Bed = bedroom, Kit = Kitchen, L = left hand, M = middle.

during occupied time. Section 5.5.2 presents the results of applying models of the impact of temperature and wind on ventilation rate, as presented for UTH in Section 5.2. This analysis did not characterise ventilation as effectively as for UTH, so Section 5.5.3 explores the similarity of the key drivers of ventilation (wind speed, direction and temperature difference) during occupied and unoccupied periods in order to explore how well the ventilation rates during occupied times are likely to be represented by the measured ventilation rates. Section 5.5.4 then compares the measured ventilation rate results and measured fan flow rates to the expectations of ventilation and fan flow rates in ADF.

Table 5.6: Proportions of occupied time, unoccupied time and ventilation rate measurements for different configurations of doors and windows in Flats A and D at CS2. Configurations with less than 5% of occupied time are grouped together and the number of these configurations is shown. WO = windows open, DO = doors open, Liv = living room, Bed = bedroom, Kit = Kitchen, L = left hand, M = middle.

Flat	**Configuration**	**Occupied Time**	**Unoccupied Time**	**Measurements**
A	WO: LivL LivM Bed; DO: All	46.3%	52.3%	69.0%
	WO: None; DO: All	20.7%	2.0%	10.3%
	WO: Bed; DO: All	9.6%	22.6%	0.0%
	WO: LivL; DO: All	5.6%	0.2%	0.0%
	Other (19)	17.8%	22.9%	20.7%
D	WO: None; DO: All	56.0%	100.0%	100.0%
	WO: None; DO: Liv Bath	36.1%	0.0%	0.0%
	WO: Kit; DO: All	5.2%	0.0%	0.0%
	Other (4)	2.7%	0.0%	0.0%

5.5.1 Different configurations of doors and windows at CS2

The results from UTH presented above showed that use of doors is a potentially important factor influencing the ventilation rates that are experienced by occupants in their homes. The monitoring of doors and windows at CS2 meant that the different configurations in which the occupants arranged their dwellings could be explored, although the ventilation rates could only be measured using the CO_2 decay technique if the dwelling was unoccupied. Additionally, the binary nature of the window and door sensors limited the findings since there is no record of the extent of opening (for example whether they were ajar or fully open). This section presents the results of the door and window opening data.

There were differences in the ways different occupants used their doors and windows. Results will be presented in detail for Flats A and D (both 1-bed flats) which exhibit contrasting window and door use patterns; the results from Flats B and C (both studio flats) will be briefly described. Table 5.6 shows the configurations of doors and windows observed at Flats A and D, the proportion of occupied and unoccupied time the dwellings spent in these configurations during the monitoring period, and the number of ΔCO_2 decays recorded in each configuration.

Table 5.6 shows that the use of doors was very different between Flats A and

D; internal doors were almost never closed at Flat A whereas the bedroom door was routinely closed in Flat D. Since the occupants of Flat A very rarely closed their doors, the effect of closing doors on ventilation rates in their home is not relevant to understanding the ventilation rates they experience at home. Conversely, the bedroom door was closed overnight in Flat D, it is likely that the ventilation rate in the bedroom is different to the ventilation rate with all doors open due to the changes in airflow throughout the flat. Although the ventilation in these times could be relevant to occupant sleep quality and next-day performance (Strøm-Tejsen et al., 2016), it was unfortunately not possible to measure the ventilation rates in this configuration using the CO_2 decay technique since the bedroom door was never left closed during unoccupied times. Whilst insights into the differences between single room and whole dwelling ventilation rates were gathered from the UTH study, further insights on this front were not possible from the CS2 dwellings since these occupants either very rarely closed internal doors, or never left them closed while the dwelling was unoccupied.

The use of windows was also very different between Flat A and D: in Flat A at least one window was open for almost 80% of occupied time and more than 95% of unoccupied time; whereas in Flat D only the kitchen window was ever opened and this was for less than 5% of the occupied time and no unoccupied time. As discussed in the previous section, the frequently open windows coupled with other factors at Flat A reduced the number ventilation rate measurements recorded in this flat. Similarly, the very small amount of unoccupied time in which Flat A had all windows closed meant that very few ventilation rate measurements were recorded in this configuration, even though this configuration is recorded for over 20% of the occupied time. There was also no unoccupied time in which Flat D had the kitchen window open, although this represented a very small proportion of the occupied time and therefore of the ventilation rates experienced by the occupant of Flat D. Darren's use of this window is discussed in Section 6.4.3 noting that it was only ever opened during exceptionally hot weather, the IAQ data from the kitchen indicated that the species measured never exceeded WHO indoor concentration guidelines (see Section 3.6.3).

The above points highlight a limitation of the natural experiment nature of this research; only those configurations in which the occupants arrange the dwelling are observed. These are the only configurations that matter for these particular participants, but not necessarily for other occupants. Additionally, the ventilation rate can only be measured in unoccupied configurations. Targeted experiments to gather relevant data from particular door and window configurations could be undertaken in future studies to overcome the lack of ventilation measurements in configurations common in occupied times but uncommon in unoccupied times. However, such work relies on a willing participant, and in this case was not possible.

Flats B and C were less extreme than Flats A and D in terms of their window use. The occupants of Flats B and C sometimes left their windows open during unoccupied periods: in Flat C windows were open for approximately 20% of occupied time and approximately 40% of unoccupied time. Brandon (the owner of Flat B and occupant until September 2019 when he let the flat to Bridget) left his windows open very often when the dwelling was unoccupied, whereas Bridget (the second occupant of Flat B who was renting from Brandon from September until the end of the monitoring period) closed the windows much more. Both Flats B and C were studio flats so only had bathroom doors, Flat B's bathroom door was very rarely closed, whereas Flat C's bathroom door was roughly evenly split between open and closed in both occupied and unoccupied times. Between 17 and 88 ventilation rate measurements were taken for each of the three most common configurations during occupied times, accounting for more than 80% of occupied time, for both Flats B and C.

In all of the flats monitored at CS2, most ΔCO_2 decays were recorded in the most common occupied configuration. Nonetheless, these measurements took place during unoccupied periods and so do not necessarily represent the conditions that occupants experienced while present since wind and temperature conditions will influence the ventilation rates. Therefore the relationship between the external drivers of ventilation, temperature and wind, and the measured ventilation rates were analysed to investigate the likely range of ventilation rates occupants experienced. This level of detail would have been extremely resource intensive and invasive for occupants if controlled experiments had taken place instead of a long-term monitoring campaign. The following section presents the analysis of the effect of temperature differences and wind on the ventilation rates measured at CS2.

5.5.2 Models of ventilation driving forces at CS2

In this section an analysis of the effect of temperature difference and wind on ventilation rates at CS2, similar to that conducted at UTH, is presented. The flats at CS2 had continuous MEV systems installed whereas UTH was naturally ventilated. MEV will affect the pressure differences in a building, and if the pressure difference driven by the MEV is large enough then this dominates and natural driving forces become insignificant. In such cases the ventilation rate would be constant, however Figure 5.9 shows considerable variation in measured ventilation rates which suggests natural driving forces remained important. As far as it was possible to determine, the fan flow rates at CS2 were constant (see Section 3.6.3 for presentation of the fan flow results); suggesting that the extract fan drove a constant pressure difference. As a result, assuming a straightforward summing of the pressure differences caused by the different driving forces as for UTH, the form of the expected total pressure difference is:

$$\Delta P = A\Delta T + Bu^2 + C, \tag{5.6}$$

where the terms of the equation are as for UTH and C is a constant pressure difference driven by the continuous MEV system. As for UTH, the flow exponent was assumed to be equal to one in the following analysis for simplification. Flow exponent values between 0.5 and 0.7 were also tried and, whilst the absolute values of the goodness of fit indicators were slightly different, the trends between models were the same.

The CS2 data was split by flat and by configuration of windows and doors and the same models were fitted as for UTH. However, none of the CS2 data was well

Table 5.7: Best fitting model for wind and temperature difference for each configuration of windows and doors at CS2 for which more than 15 measurements were recorded. Goodness of fit of the models was assessed using the adjusted R^2 and AIC values, where these metrics did not agree on the best performing model, both models have been given and the model preferred by the AIC value is indicated with a *. Cases where none of the tested models gave an adjusted R^2 better than 0.1 are indicated by -.

Flat	Configuration	Measurements	Best model	Adjusted R^2
B	WO: None; DO: All	69	$\lvert\Delta T\rvert+u^2+u\,cos(\theta+\gamma)+C$	0.44
D	WO: None; DO: All	162	$\lvert\Delta T\rvert+u+cos(\theta+\gamma)+C$	0.15
C	WO: None; DO: All	60	$\lvert\Delta T\rvert+u+u\,cos(\theta+\gamma)+C$	0.30
C	WO: None; DO: None	87	$\lvert\Delta T\rvert+u^2+u\,cos(\theta+\gamma)+C$	0.13
C*	WO: None; DO: None*	87	u^2+C	0.12
A	WO: LivL LivM Bed; DO: All	20	$u\,cos(\theta+\gamma)+C$	0.38
B	WO: LivR; DO: All	47	$\lvert\Delta T\rvert+u^2+u\,cos(\theta+\gamma)+C$	0.37
B	WO: All; DO: All	19	-	-
C	WO: All; DO: All	17	-	-

described by any of these models, for example the maximum adjusted R^2 value was 0.44. Table 5.7 shows the best fitting model for each configuration at CS2 with over 15 measurements, goodness of fit was judged using the adjusted R^2 and AIC - where these did not agree both models are given and are marked in the table. Table 5.7 gives the adjusted R^2 value but not the AIC values since the absolute value of the AIC is not meaningful for comparing models fitted with different data.

Table 5.7 shows that, as at UTH, the best performing models often combine all three explanatory variables: wind speed, wind direction and temperature difference, however the performance of the models is much worse than observed at UTH. As discussed above, if the pressure difference was dominated by the mechanical extract ventilation then the wind and temperature difference would have little influence on the ventilation rate. However, if this were the case, C would be much larger than the terms involving wind or temperature difference and the ventilation rate would be fairly constant. The models attempted and spread in measured ventilation rates did not indicate that this was the case at CS2.

There are several possible reasons that the models perform worse at CS2 than UTH. Firstly, a simple summing of the pressure differences due to different driving forces without considering interacting effects and leakage locations may not be appropriate for these flats. For example, it is possible that if the wind causes back pressure in the extract ducts then this may reduce discharge of air from the MEV system and the ventilation rate; the models presented above have no mechanism for taking such an effect into account. Nabinger and Persily (2008) studied the effect of temperature difference and wind speed on ventilation rate in a manufactured test house in the USA, the test house was equipped with a forced air HVAC system - these are common in North America but much less so in Europe. Combining SF_6 decay measurements and modelling in CONTAM, Nabinger and Persily (2008) were able to show that the forced air HVAC system 'competed' with the stack effect at positive temperature differences resulting in lower ventilation rates than if the HVAC system was switched off. However, the ventilation system was switched off at Flat B meaning that this flat was naturally ventilated, the models did not perform significantly better for this flat.

The wind data used for CS2 was also collected much further away from the case study site (approximately 20 miles) than the wind data for UTH (approximately 5 miles). It is likely that the complex topography of the urban environment around CS2 with many high-rise buildings meant that the wind conditions were significantly different to the wind at the relatively unobstructed area around the Heathrow Airport measurement site. It is therefore possible that the Heathrow wind data does not adequately represent the wind conditions affecting the ventilation rate at CS2. Wind data from a weather station less than 10 miles from CS2 and closer to central London was also investigated, however this was clearly affected by local shielding as some wind directions were very strongly preferred and therefore was not appropriate for further study. Surprisingly, despite these issues, in one case (Flat A, WO: LivL-LivM-Bed; DO: All) a model including only wind data was the best of the models tried and in another (Flat C, WO: None; DO: None) the best model according to the AIC value included only wind data.

The results show that the same configuration of doors and windows in different flats do not result in the same models fitting the data well, nor is the goodness of fit similar for similar configurations. With all windows closed in Flat C, the best performing model is different between bathroom door closed and open (WO: None; DO: None and WO: None; DO: All), it is not clear why closing the bathroom door would significantly affect the goodness of fit of the best model, nor the form of the best performing model. The results from all the models tried have not been presented due to the volume of results, however the best performing single variable model (models 1-8 in Table 5.3) indicated that different explanatory variables were most significant for different configurations. Additionally, the values of γ for which the models performed best did not correspond to the exposed façade of the flats, unlike at UTH.

The analysis of the effect of wind and temperature difference on ventilation rates at CS2 did not return any strong relationships. This meant that none of the presented models can be used to estimate the ventilation rates experienced during occupied times based on the weather conditions and configuration of doors and windows. However, a large number of measurements of ventilation rate were collected over many different weather conditions enabling the assessment of the similarity of the distributions of wind and temperature differences during measurement times and occupied times. Comparison of the distributions of weather conditions during occupied and measurement times supports the interpretation of ventilation rate measurements in each condition, as discussed below.

5.5.3 Distributions of temperature, wind and ventilation rates and adequacy of ventilation

The distributions of wind and temperature differences during measurement periods and occupied periods were compared. The measurement period ran from July to

December so the results are expected to be broadly reflective of conditions experienced throughout the year. This analysis was used to indicate whether the occupants are likely to experience adequate ventilation rates with different configurations of doors and windows.

The distributions of temperature difference, wind speed and direction during measurement and occupied periods were compared using a Mann-Whitney U-test for each configuration with over 15 measurements for each flat. The Mann-Whitney U-test is a non-parametric test with the null hypothesis that two samples are drawn from the same parent distribution (Weaver et al., 2017); the null hypothesis was rejected if the P-value was less than 0.05. The sine of the wind direction was used since this data was circular. Figure 5.10 presents the results of this analysis for Flat B as an example, showing histograms of the temperature difference, wind speed and wind direction for measurement and occupied periods along with the p-value from the Mann-Whitney U-test to show whether this indicates that the distributions are statistically different. The results for the remaining Flats are discussed but not presented in full as the key points can be readily seen in the example from Flat B. Figures equivalent to Figure 5.10 are given in Appendix C for Flats A, C and D.

Figure 5.10 shows that for the configuration ‘WO: None; DO: All’ following the Mann-Whitney U-test there is not enough evidence to reject the hypothesis that the measurement and occupied distributions are drawn from the same distribution for all three tested variables. In such cases it is reasonable to assume that the distribution of ventilation rates measured are representative of the ventilation rates that the occupant has experienced in this configuration during the monitoring period, in the absence of other known factors that are likely to significantly affect ventilation rate. For this configuration, 91.5% of the measured ventilation rates are below 0.5 ach and the median ventilation rate is 0.24 ach; it is therefore likely that for the vast majority of time that the occupant has spent in this configuration they have been experiencing inadequate ventilation rates. It should be noted that the continuous MEV system was switched off in Flat B throughout the monitoring period.

Figure 5.10 shows that in other cases the null hypothesis is rejected for one

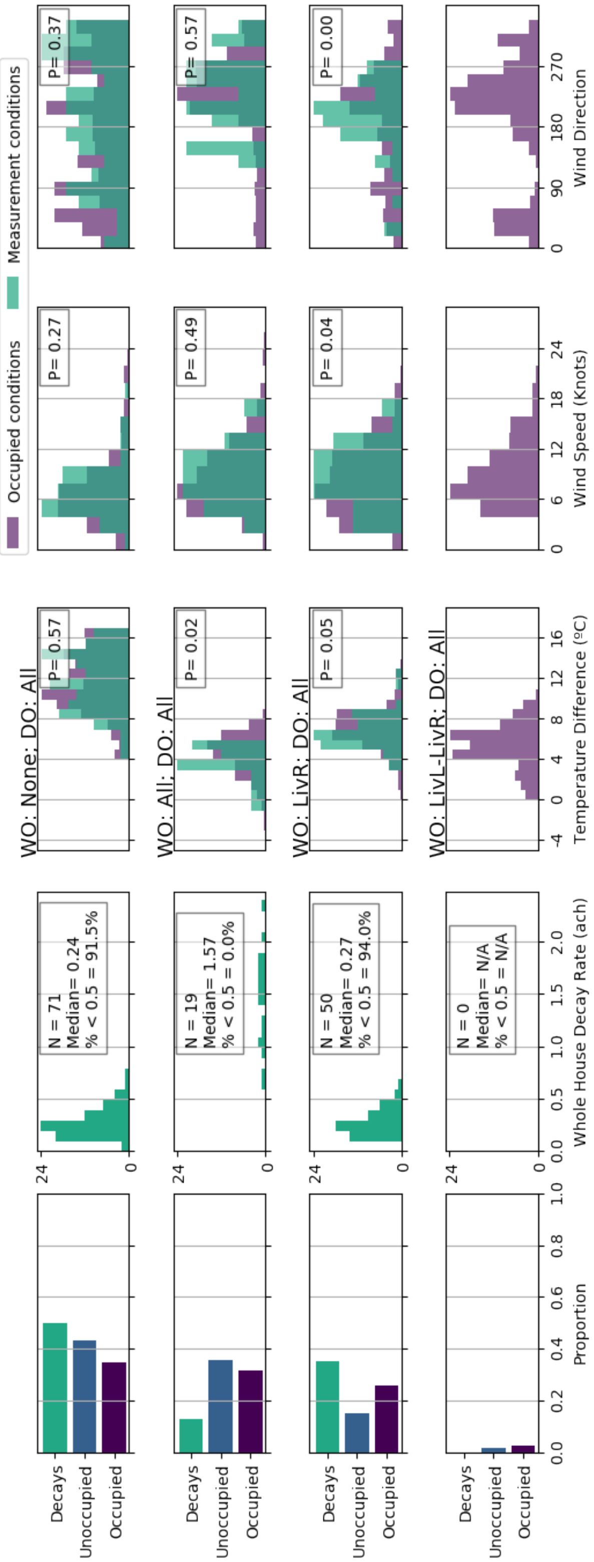


Figure 5.10: Results for the four most common configurations of doors and windows from Flat B at CS2. For each configuration the proportion of measurements, unoccupied time and occupied time recorded is shown in the left figure; the distribution of measured ventilation rates in the second left figure; the distribution of temperature differences, wind speed and wind direction during occupied and ventilation measurement periods and the p-value from the Mann-Whitney U-test are shown in the final three plots.

or more of the variables: this means the distributions are not drawn from the same parent distribution according to the Mann-Whitney U-test. For example the null hypothesis is rejected for temperature difference in the configuration 'WO: All; DO: All', the histograms show that the range of conditions during measurement and occupied times is broadly similar albeit with a shift towards lower temperature differences during measurement times. The median temperature difference for measurement periods is 3.7°C and 4.8°C for occupied periods for this configuration. Thus it is not expected that the distribution of ventilation rates in occupied times is the same as those measured, but the differences are modest. In particular the qualitative interpretation that ventilation rates are often adequate during occupied times based on the measured results remains reasonable given the wide range of weather conditions in which the ventilation rates have been measured, even if the proportion of time this is likely to be true for cannot be quantified.

For the rest of the flats there were no further configurations in which the null hypothesis could be rejected for all three weather variables. As above, the range of weather conditions were similar during measurement and occupied periods in all cases, supporting the qualitative interpretation of often adequate or inadequate ventilation rates during particular configurations. Figure 5.9 shows box plots of the ventilation rates measured in different configurations. The measured results were almost always lower than 0.5 ach in Flats B, C and D with windows closed, this configuration represents over 70% of the occupied time for these flats. The results with more than one window open were almost always greater than 0.5 ach for all flats, as expected. However, the results are very different in terms of how much occupied time is represented by such configurations: almost 50% for flat A, close to 30% for Flat B and less than 5% for Flat C (more than one window open was never recorded at Flat D).

This analysis of the representativeness of the measured ventilation rates to those experienced during occupied periods adds a layer of detail not usually explored in empirical studies of ventilation in occupied homes. Such analysis may be particularly important in interpreting results generated using CO_2 as a tracer gas, since conditions are placed on the occupancy status during measurement periods for all experimental configurations. Future research could combine such analysis with schedules of pollutant profiles, to explore IAQ during occupied hours and issues around the ventilation rate required at different times.

The following section explores the differences between ideal performance of the ventilation system as set out in ADF and the measured performance in these dwellings as-built and as-occupied.

5.5.4 Comparing the ventilation performance at CS2 to the planned performance according to ADF

The section above showed that the ventilation rates measured at CS2 with all windows closed were usually below 0.5 ach, often taken to be a threshold for adequate ventilation rate. The flats had a continuous mechanical extract ventilation (MEV) system (ADF system 3), ADF gives a whole dwelling ventilation rate which is required to be continuously delivered by the ventilation system, this should be achieved with windows closed. The measured flow rates of the continuous MEV were presented in Section 3.6.3, where it was seen that the sum of the extract rates of the fans throughout each dwelling was much larger than the whole dwelling ventilation rate required by ADF. Table 5.8 shows the ADF whole dwelling ventilation rate, the sum of the measured extract rates and the conversion of this into ach assuming the whole volume of the flat takes part in air exchange; the median, maximum and minimum measured ventilation rates with all windows closed is also presented for comparison (Flat A is not included because there were no measurements with all windows closed). As discussed in Section 3.6.3 the flow rate of the bathroom fan in Flat C almost doubled after the occupant cleaned around the ceiling terminal; the total fan flow rate presented in Table 5.8 is prior to the fan cleaning since the ventilation rate measurements all took place before the cleaning.

Table 5.8 shows a considerable discrepancy between the ADF whole dwelling ventilation rates, the total measured flow rate from the continuous MEV system and the measured whole dwelling ventilation rates. One possible reason for the discrepancy between the measured flow rates and measured ventilation rates could

Table 5.8: The whole dwelling ventilation rate required by ADF, the measured total fan flow rate, and the minimum, median and maximum measured ventilation rates for configurations with all windows closed for all flats at CS2. The total fan flow rate is presented for Flat B, although the system was switched off throughout the monitoring period, the total fan flow rate for Flat C is prior to the cleaning of the bathroom terminal.

Flat	ADF whole dwelling ventilation rate (l/s; ach)	Total fan extract rate (l/s; ach)	Minimum measured ventilation rate (l/s; ach)	Median measured ventilation rate (l/s; ach)	Maximum measured ventilation rate (l/s; ach)
A	15; 0.44	31; 0.9	-	-	-
B	13; 0.56	25; 1.1	1; 0.06	6; 0.24	16; 0.71
C	13; 0.56	25; 1.1	2; 0.08	10; 0.42	30; 1.29
D	13; 0.45	19; 0.7	3; 0.1	12; 0.41	32; 1.1

be that the continuous MEV system is not delivering the expected volume of fresh air throughout the flats. Potential causes of this issue include the extract air leaking into the flat before reaching the outdoor terminal, or the outdoor terminal could be close to an air inlet and therefore incoming air could be partly made up of extract air, the infiltrating air may not be fully mixing with the full volume of air in the flat and the locations of the CO_2 sensors may be outside the stream of outdoor air, or a mixture of all of the above is possible. It was not possible to empirically investigate these possibilities. However, the planned ventilation drawings showed that the continuous MEV duct was routed to terminate directly above one of the windows very close to the trickle vent on this window. Additionally, the ventilation commissioning certificates indicated that the ducts were not fully connected to the external wall as planned. These two issues may have contributed to the system's failure to deliver the expected volume of fresh air throughout the flats. Regardless of what causes this issue, the majority of measured ventilation rates were significantly below the ADF whole dwelling ventilation rates in all cases.

The as-built and as-occupied ventilation system was also not used in the manner planned with regards to the trickle vents. As discussed in Section 3.6.3 all of the flats had more installed trickle ventilation effective area than required according to System 3 in ADF. However, on none of the occasions on which the researcher visited the dwellings were any of the trickle vents open, despite the ADF intention that trickle vents are always open. The results of the qualitative interviews, see Section 6.4.1.5, suggested that trickle vents may have occasionally been opened in Flats A and C, however the timing of this is not known so any change in ventilation rate caused by this is not known. Additionally, the inside of the trickle vents were visibly dusty, although it is not known to what extent the dust would impede the flow of air through open trickle vents. Unfortunately, without occupant intervention or experimental testing, which were not possible in this field study, it was not possible to determine the impact of opening the trickle vents on the ventilation rate in these dwellings.

Overall, the results show that the ventilation system as-installed and operated is unable to reliably provide adequate ventilation when all windows are closed. Occupants in these dwellings need to open windows to reliably obtain adequate airflow. The implications of this finding, along with all the results from CS2 and UTH, are discussed in the following section.

5.6 Summary

This chapter has presented the results gathered at UTH and CS2 using the CO_2 decay analysis method and occupancy algorithm described in Chapter 4. This section gives an overview of the findings from both case studies and discusses their implications. Firstly, Section 5.6.1 discusses the implementation of the method developed in Chapter 4, highlighting its strengths and limitations and how it might usefully be used in future research. Section 5.6.2 discusses the results of the models of ventilation rate and weather developed in this chapter. Finally, the long term monitoring study undertaken in this research has brought insights into the effect of simple occupant actions, with implications for health research and policy, these are discussed in the final sections of this chapter, prior to further consideration and discussion in Chapters 6 and 7.

5.6.1 Measurement of ventilation in occupied dwellings

The ventilation measurement method and occupancy algorithm presented in Chapter 4 were successfully implemented at CS2. The occupancy algorithm was used to analyse large volumes of data from the extended measurement campaign at CS2. In three of the four occupied dwellings over 100 measurements of ventilation rate were recorded. This method enabled the investigation of the varying nature of ventilation rate, how this relates to the occupants' use of the property and provided detailed insights into the use of doors and windows in occupied dwellings. It was possible to gain an insight into how the occupants use the dwelling when they are present, and whether their use of internal doors meant that the dwelling is likely to behave as one single zone or if they are likely to experience different ventilation rates depending which room they are in during occupied times. Additionally, by combining the ventilation rate results with the results of the OSA, it was possible to assess whether the measured ventilation rates were likely to reflect those during occupied times. In most cases the distributions of weather conditions were not identical, although the range of conditions was similar, this helps to characterise the uncertainties and limitations of extrapolating the measured results to those experienced in occupied times. Such characterisation may be particularly important for ventilation measurement methods which place requirements on the occupancy status of the measured space (particularly where CO_2 is used as a tracer gas).

There were important limitations to the method applied in this research. Firstly, the analysis of the data assumed that the dwellings at CS2 could adequately be described as single zones, this was discussed in the previous chapter (Section 4.2.2). For the dwellings measured at CS2 this appeared to be a reasonable assumption most of the time: internal doors were very rarely closed during measurement periods and three of the four dwellings often reached the homogeneity requirements set out in Chapter 4. More complex dwellings, with multiple stories or many more rooms, may be more difficult to study using this method since metabolically generated CO_2 may less frequently be homogeneous. Additionally, the evidence of flow between adjacent dwellings presented in this research highlights that the flats were not necessarily single zones isolated from the rest of the building. This has potentially affected the results, the extent of this is not known but is likely to be small since it was rare to identify occasions that the ΔCO_2 concentrations increased in unoccupied flats indicating leakage from adjacent dwellings.

Secondly, the method was limited by the configuration in which the occupants leave the dwelling unoccupied and by the amount of CO_2 generated by the occupants. This was particularly seen to limit the results in Flats A and D. The windows were very often open during unoccupied periods and the homogeneity conditions were not often met in Flat A, which limited the number of ventilation measurements and the insights that could be drawn about the conditions experienced by these occupants. Whereas in Flat D, the dwelling was only ever unoccupied in one configuration - this was the most frequent occupied configuration, but the configuration in which the occupant slept, with the bedroom door closed, could not be analysed. This method would ideally be supplemented by a series of targeted experiments to characterise ventilation performance under test conditions in a range of configurations. However, such work is disruptive, requiring a willing participant, and in this case was not possible.

The combination of long-term monitoring, measurement and analysis methods used here is a promising tool for further research. At present it is unusual to collect data over an extended period to enable characterisation of the use of doors and windows and the associated ventilation rates. However, the cost of the equipment and management of the measurement campaign are important restrictions to the future application of this method. The time required for managing the monitoring campaign and interpretation of the analysis results is also significant, although the OSA and analysis algorithm significantly reduce the time required to analyse metabolic CO_2 data for ventilation rate measurements in occupied dwellings. Gathering these results using controlled experimental methods would have required considerable research time and equipment, and much greater burden to participants if taking place in an occupied dwelling. The method may support further detailed studies into the ventilation rates in occupied dwellings, addressing a current gap in the empirical evidence. More research of this kind could provide empirical evidence to support improvements to policy and practice to deliver healthy living environments at low energy cost. Such evidence also cross-references and provides input data to models of ventilation performance, for the operation of test dwellings and laboratory testing. Increased availability and ease of verification and testing in real dwellings would be helpful for ensuring models of ventilation, and its consequent effect on IAQ, target the most relevant dwelling configurations for different households.

5.6.2 Ventilation and weather conditions

The relationship between environmental factors and measured ventilation rates was investigated. At UTH it was possible to build a model of ventilation based on simple relationships between pressure, temperature difference, wind speed and direction but at CS2 this was not possible. MEV systems drive a pressure difference across the building envelope, this can dominate the natural driving forces from temperature difference and wind resulting in a nominally constant ventilation rate. However, the ventilation rates at CS2 were highly variable, meaning that the MEV system combined with (closed) trickle vents did not provide constant ventilation rates, but nor did the ventilation rates vary according to the simple relationships developed for UTH. Factors contributing to this may include the effect of back pressure on the MEV from wind incident on the façade of the building. Additionally, the simple models which worked well at UTH did not work well for Flat B where the MEV was switched off. This could be because the wind data for CS2 came from a weather station much further away than at UTH, and the CS2 local environment was much more urban with a high density of high-rise buildings, this is likely to have affected the representativeness of the weather station wind to the local wind conditions at CS2.

The results of the ventilation models at UTH showed that the wind direction was a much more important explanatory variable than wind speed or temperature difference for measurements with the trickle vents open compared to trickle vents closed. In addition, it is notable that previous empirical research investigating wind, temperature difference and ventilation rates has often neglected wind direction as an explanatory variable. The research presented here suggests that wind direction may be a particularly important factor when trickle vents are used. Given that trickle vents are now widely installed in the UK dwelling stock, further research combining empirical work, such as that presented here, with modelling may help to increase understanding of ventilation in dwellings as-built.

5.6.3 Ventilation and simple occupant actions

UTH had an air permeability of 15.1 $m^3/hr/m^2$ at 50Pa, with trickle vents open the whole dwelling ventilation rate was 0.8 ach ± 0.1 ach, while the mean ventilation rate in one room with the door closed was 0.3 ach, standard deviation 0.1 ach (N = 62). UTH as a whole was therefore likely to have high heat loss, but inadequate IAQ may be experienced in this single room when the door is closed. Although the dwelling had high air permeability, it cannot be assumed that the ventilation is adequate in rooms with their doors closed. The difference between whole house and single room ventilation rates identified at UTH may be replicated in other dwellings in the stock as the locations of air leakage paths at UTH were not unusual (Stephen, 2000) and the air permeability was typical for a building of its age (Perera and Parkins, 1992). The specific ventilation rates and impact of the use of trickle vents and internal doors will vary property-by-property and it was not possible to investigate the effect of door closure on ventilation rates at CS2 as none of the occupants left doors closed while their dwelling was unoccupied. However, more modern dwellings are built with a lower total air permeability and this issue may become more acute in these buildings as the ventilation through infiltration will be smaller. Similarly, increasing numbers of dwellings like UTH will be retrofitted in the coming years to improve their energy efficiency, this will likely reduce their air permeability. As a result, single room ventilation rates could be even lower leading to a corresponding increase in indoor pollutant exposure depending on the pollutant sources and strengths and on the locations of air leakage pathways. This highlights the need to consider how homes are operated as-occupied in the context of both new-build and retrofit ventilation strategies.

The closure of trickle vents at UTH further lowered the single room ventilation rate, but the whole dwelling ventilation rate continued to indicate high heat loss. This compounds the complexities above, as this suggests that the appropriateness of trickle vents depends on the configuration of the dwelling. The dwellings at

CS2 had trickle vents closed on every occasion that they were visited and previous research has shown that trickle vents are often closed in occupied homes (Crump et al., 2005; Sharpe et al., 2015). This is in contrast with the statement in ADF that trickle vents are intended to be permanently open (HMG, 2010b).

Whilst it is expected that simple actions such as use of trickle vents, internal doors and windows will have a significant impact on ventilation rates, there is little empirical research in occupied dwellings that addresses this. The research at CS2 highlighted the importance of further research to investigate such issues; the dwellings studied were physically very similar but the occupants' use of the windows had a dramatic influence on whether or not the ventilation rates were likely to be adequate during occupied times. Only four dwellings were studied, but all showed very different use of windows and doors. The results at UTH showed that the spatial scale over which ventilation is measured can influence whether the ventilation appears to be adequate. The detailed picture of ventilation, window and door use and differences between occupied and unoccupied times investigated in this research is unusual. Further measurement of ventilation in the changing conditions of occupied homes using methods such as those employed for this research will improve understanding of how occupants interact with their homes and the effect of this on the ventilation conditions they experience. Such research would also improve assumptions in models of ventilation and pollution exposure as well as providing an experimental comparison for modelled results. The results at UTH and CS2 imply that simple occupant actions can have a significant impact on ventilation rates and highlights the challenge of designing ventilation strategies and guidance which ensure appropriate ventilation in occupied dwellings. The following chapter presents the results of the qualitative investigation of the participants' social practices relating to ventilation in their homes and the ways this conforms and conflicts with the intentions in ADF, including the occupants' use of trickle vents, doors and windows.

5.6.4 Implications for health

There are potential health implications to the ventilation rates people experience in their homes, most obviously in the way in which they relate to personal exposures to pollutants. Current research attempting to characterize the relationship between ventilation rate and health has often treated ventilation in the home as though it is a single value (Fisk, 2018; Sundell et al., 2011), while the results presented here show that people are likely to experience a wide variety of different ventilation rates depending on the configuration of doors and windows, the weather and the location of the occupants within the dwelling. Fisk (2018) systematically reviewed the literature regarding the effect of ventilation on health and concluded that the evidence suggests that increased ventilation rate is associated with better health outcomes, although it was not possible to identify a threshold ventilation rate at which this happens. Fisk identifies that the studies reviewed used inconsistent ventilation metrics such as ventilation per person, per floor area or air changes per hour and that this complicated the analysis. From the results presented here it seems plausible that the reduction to a single value of many different ventilation rates experienced in different configurations of windows and doors during occupied and unoccupied times could also be a confounding variable. For example, a difference in configuration of door and window opening when occupied compared to when unoccupied could lead to significant differences in ventilation rate, but only the former is likely to have health implications. A method that enables the characterisation of door and window configurations during occupied and unoccupied periods, and then links this to ventilation rates observed in those configurations, may enable greater insight into the impact of ventilation rates on health outcomes.

More work to disentangle ventilation, pollutant sources, occupant locations and exposure time could help to provide a more coherent understanding of the link between ventilation and health. McGrath et al. (2017) modelled personal exposure to indoor pollutants for different occupants with various indoor pollution location and source strength profiles, door closures and occupant location profiles which were to an extent based on time of use surveys. They found that some occupants were exposed to significantly worse pollution than others in the same dwelling. Similarly, Bekö et al. (2016) argued that temporal variations in pollutant source profiles are often not adequately addressed by ventilation standards which require that particular ventilation rates are met at all times in all spaces. Further work such as that presented here could help to understand the use of internal doors, windows and ventilation rates in different configurations so that such studies can better represent as-occupied conditions.

5.6.5 Policy implications

Several of the findings presented in this chapter have important policy implications. The current building regulations do not adequately account for differences between single room and whole dwelling ventilation rates as identified at UTH. Strategies which may improve individual room ventilation rates, without increasing whole house ventilation, include increased undercuts beneath doors and vents between rooms. Undercuts are required for new buildings, but are only required in existing buildings when new wet rooms are fitted. Amending the regulations such that undercuts or vents between rooms are required when doors are replaced or major building work takes place may improve individual room ventilation rates from a technical perspective. However, there are potential occupant acceptability issues with these measures: they may increase cold draughts, noise transmission and the spread of smells around the dwelling. Fire safety concerns must also be addressed: between wall vents should not be placed in fire-resisting walls and should only be placed at low levels to reduce smoke transmission in the event of a fire; additionally, fire doors are rated for a particular depth of undercut so these may need to be retested if undercuts are adjusted. Such issues are likely to be increasingly important as more dwellings undergo energy efficiency retrofit, this often decreases air permeability. When an energy efficiency retrofit takes place it is required that existing ventilation strategies are reviewed and additional ventilation is provided if the ventilation is inadequate (BSI, 2019), this includes providing undercuts where these are missing, which will help to improve whole dwelling ventilation in such cases.

Potential issues with ventilation system commissioning were raised by the results from the dwellings at CS2 showing that configurations with windows closed were very likely to have inadequate ventilation rates most of the time. This was in contrast with the measured flow rates of the extract system which in Flats A, C and D appeared to be continuously running at flow rates which were far higher than the ventilation rates measured (the system was switched off throughout the monitoring in Flat B). Despite the high measured flow rates, the ventilation system was not able to provide the expected ventilation throughout the flats. This finding raises a regulatory issue: current ventilation system commissioning uses fan flow rates to confirm the adequate functioning of mechanical ventilation after installation (BSRIA, 2015), this is not sensitive to situations in which the delivered mechanical ventilation flow rate is not reflective of the ventilation rate in the occupied spaces. The prevalence of this issue in the wider stock is not known, but the potential for such issues indicates that further research is required.

A key and unexpected finding of this study was the presence of airflow between the two adjacent dwellings in this study. Flow between dwellings is potentially important for a number of reasons, such as fire safety and indoor air quality, as discussed above. It was not possible to determine if this airflow was from a leakage pathway large enough to breach fire safety regulations. Investigation into potential air leakage rates between dwellings and the implications of this is not an active area of research, at least in the ventilation research. Leakage between homes has serious potential implications for fire safety, spread of pollutants and occupant satisfaction due to spread of smells between dwellings; further investigation of this issue more widely in the stock would bring valuable insight.

Finally, potential issues relating to the maintenance of ventilation systems were raised: cleaning the bathroom extract terminal in Flat C at CS2 significantly increased the measured flow rate. There is very little current research on the requirements for and consequences of maintenance for ventilation systems, this result suggests further research is required to assess the prevalence and magnitude of such problems. Such research may also investigate the effect of dust impeding airflow through trickle vents: dust was observed at CS2 and previous authors have noted other likely causes of reduced airflow through vents (for example having been painted over or installed incorrectly Fox (2008) and Sinnott (2016)), although these studies have not quantified the impact of these issues.

This chapter reported on the measured ventilation rates in CS2 and UTH, exploring the role that the occupants play in shaping the ventilation rates they experience through simple actions. The following chapter explores the occupants' social practices related to ventilation at home, with an emphasis on comparing their practices to the intentions set out in ADF regarding use of the ventilation system. This helps to illuminate some of the issues raised in this chapter, including the occupants' differing use of windows, doors, trickle vents and the continuous MEV.

Chapter 6

Manipulating Air, Maintenance of Ventilation Equipment and ADF

The previous two chapters have discussed the technical findings of the study, the present chapter turns to the social findings. The literature review in Section 2.4 showed how previous work which has measured ventilation has tended to give minimal attention to the occupants of the building or to study their interactions with the building through structured questionnaires with little room for nuances to be discovered. It was then argued in Section 2.5 that Social Practice Theory (SPT) can be a useful lens through which to study everyday goings on with a strong link to the influence of material arrangements. Previous studies taking an SPT approach to study practices involving ventilation were then discussed in Section 2.5.2, in particular Gram-Hanssen (2010a), Hauge (2013), Royston (2014), and Behar (2016). The final research question asked how the participants' practices around ventilation differed to the intentions set out in Approved Document F (ADF) (HMG, 2013b).

This chapter compares the ventilation practices of the participants at CS2 to the intentions of ADF. It will be shown that the air in homes is socially significant and that practices around manipulating the air can be informed by this. Air and manipulating air are understood in broad terms, involving properties and characteristics including temperature, humidity, smells and sounds carried through open windows. The routes by which the air becomes apparent and is manipulated with the aim of improving indoor conditions are discussed, the extent to which various technologies are involved in these practices is drawn out. The limited extent to which the participants had institutionalised knowledge or rules around the ventilation system and indoor air quality is also discussed. This social context helps to show the ways that the participants affect ventilation and the need for ventilation at CS2, and the ways this differs from the stated intentions in ADF. The majority of this chapter focuses on the everyday ventilation practices of the participants, but the extent to which ADF, manufacturers and the participants consider maintenance of the system is discussed in the final part of the chapter since the technical results in the previous chapter indicated that maintenance could be important.

This chapter makes reference to relevant literature throughout, Braun and Clarke (2013) assert that this approach can be useful where there are strong links to existing research. The existing SPT literature has discussed many of the issues identified here in relation to the participants' social practices, albeit sometimes in different contexts. It is useful to highlight where similarities exist between the participants' practices and other domestic practices identified by previous authors. This chapter takes the additional step of comparing these practices with the implicit assumptions ADF makes about the ways occupants will ventilate their homes. This chapter starts by briefly introducing the participants and reiterating the Gram-Hanssen (2010a) SPT framework used to analyse the qualitative data. The ventilation strategy set out in ADF is presented in Section 6.3, including the stated purpose of ventilation, the remit of the document and how ADF splits ventilation into three different categories. This begins to show how ADF intends occupants to ventilate their homes and the factors that are considered to influence this, this section also shows how the ventilation strategy in ADF can be translated into the SPT elements. Section 6.4 then presents a detailed comparison of the participants' practices of manipulating the air with ADF's intentions for ventilation in homes with the same ventilation strategy as at CS2. A short comparison between the participants' practices related to the maintenance of the ventilation system and how maintenance is referred to in ADF is given in Section 6.5, before the chapter is summarised in Section 6.6.

6.1 Introducing the participants

Each of the participants are briefly introduced here to give context to the following discussion of their practices. The participants have been given pseudonyms to protect their identity, these pseudonyms begin with the same letter as the letter used to identify the flat that they live in.

Aaron and Alice bought Flat A in 2016 and live with their dog Alfie. Aaron and Alice both work full time, Aaron works in an office Monday - Friday while Alice usually works from home three days a week. Alfie's schedule is very similar to Alice's in terms of time spent in the flat. Flat A is at the back of the building, the windows look out on trees, a railway and a stream. All other flats studied were at the front of the building and look onto a drive and turning-circle in front of the building, beyond which is a smaller building and then a major road (A-road).

Brandon lived in Flat B until October 2019, he then let the flat to Bridget for several months. Brandon bought his flat over two years ago and had previously let the flat for a period of time in 2017. Brandon had a variable schedule, sometimes working at home, sometimes in an office in London and sometimes abroad. Bridget was an EU student who had moved to London from her home country in September, she went to University most week days and spent time in the flat studying as well as relaxing.

Cal bought Flat C in 2018, and this is the first place he has owned and the first place he has lived without flatmates. Cal works a 9 to 5 job in an office in London.

Darren is renting Flat D, he had lived there for almost a year at the time of the interview and had recently extended his lease for a further year. Darren works at an office in London most week days.

All of the participants were university graduates, except Bridget who was studying for her degree.

6.2 A brief reminder of the SPT framework

The analysis of the participants' practices followed Gram-Hanssen's (2010a) social practice theory framework. This has been described previously in Section 3.4.1 but the four elements in Gram-Hanssen's formulation as interpreted in this work are briefly outlined here again for clarity:

- **Meanings, engagements.** This is about what the practitioners want, or the goal they are pursuing.
- **Practical understandings, embodied habits, know-how.** This element includes the practical doings that the practitioners take in order to service their meanings and engagements, knowing how to affect conditions in the desired way and how the body knows something needs to be done. This includes the action that is required as well as the recognition or perception that action is required.
- **Knowledge, rules.** Rules are requirements placed on the practitioners, and knowledge is formal information.
- **Products, things, technologies.** These are the physical things that the practitioners interact with, these can enable and constrain particular courses of action.

The know-how element has also been informed by Madsen and Gram-Hanssen (2017), which discusses bodily sensations as communicating information about the outside world, in this way bodily sensations are part of knowing whether something needs to be done about the environment in which we find ourselves.

In analysing the participants' social practices involving ventilation it was clear that to focus only on ventilation, the replacement of indoor air with outdoor air, would be to inaccurately represent the participants' practices. The participants' practices included steps to control ventilation, but these steps were part of a wider picture which involved seeking to control many characteristics of the air in their homes, not just the amount of outdoor air replacing indoor air.

For this reason, it is helpful to consider the approach in Cass and Faulconbridge (2017), which draws on Schatzki's distinction between 'dispersed' and 'integrative' practices. Dispersed practices are small scale actions, which are commonplace and take place in different contexts and their meaning may be altered when performed in different circumstances. Integrative practices are wider practices which constitute and are part of particular domains of life, these might include farming, business and shopping practices. Performances related to ventilation can then be understood as 'dispersed' practices, which can appear as part of a wide variety of other practices, where the aim might or might not be related to increasing the rate of replacement of indoor air with outdoor air in a space.

The limits of the social enquiry were drawn around the actions that the participants took which affected ventilation or the need for ventilation, whether this was conscious or not. For this reason the practice has been interpreted as a dispersed practice of manipulating the air, the ways that the participants seek to affect, manage or influence different characteristics of the air in their home, these characteristics are taken to include temperature, smell, humidity or sounds carried through open windows. Interpreting this as the practice of interest allows ventilation to be included as one of the steps the participants may take to affect characteristics of the air, but not the only actions of interest.

The following section discusses how the ventilation strategy and systems in ADF can be interpreted using the SPT framework just described.

6.3 ADF ventilation strategy

ADF sets out a ventilation strategy and four ventilation systems. The strategy gives an overall framework for ventilation. Details of four ventilation systems which are assumed to comply with the strategy are also given (these were presented in Section 2.3), this provides technical details, such as flow rates and sizing of the technologies used in each of these systems. These are assumed to meet the Building Regulations requirement that 'adequate means of ventilation [are] provided for the people in the building' (HMG, 2010d).

This section presents the overall ventilation strategy set out in ADF and considers how this strategy can be interpreted within the SPT framework set out above.

6.3.1 What is ventilation for?

According to ADF, ‘ventilation is simply the removal of “stale” indoor air from a building and its replacement with “fresh” outside air. It is assumed within the Approved Document that the outside air is of reasonable quality’ (HMG, 2013b, p. 13). This sets up the dominant framework in ADF, that the indoor environment is improved by dilution with outdoor air. This can also be translated into the SPT framework as the overall meaning of ventilation being the provision of ‘fresh’ outdoor air and removal of ‘stale’ indoor air.

ADF gives four reasons that ventilation is required: provision of outside air for breathing, for dilution and removal of airborne pollutants including odours, for controlling excess humidity and for providing air for fuel burning appliances. Again these reasons can be translated as meanings or goals in the SPT framework. These focus on controlling the constituents of indoor air or airborne pollutants.

However, other environmental parameters, such as temperature and noise, are affected by external air and how it enters a building. Some of these are acknowledged in ADF, for example: ‘ventilation may also provide a means to control thermal comfort but this is not controlled under the Building Regulations’ (HMG, 2013b, p. 13). The participants used the windows in this way, for example Aaron explained why he liked to open windows in the summer:

> AARON there’s a really nice breeze coming through the flat [when the living room window is wide open], but I guess we only get that in the summer because it would be Baltic if we opened that window in the winter.

Although ADF explicitly acknowledges that thermal comfort may be influenced by ventilation, this suggests that the external environment provides a desirable quality in providing thermal comfort. However, there could be a conflict between the external environment being thermally uncomfortable in the winter (whereby ventilation would not provide a means to control thermal comfort) and the intended use of the ventilation system. Such effects clearly did affect Aaron’s use of the windows.

While the effect of thermal discomfort was not addressed, ADF does note that a noisy external environment may prevent occupants from opening windows for ventilation, and it is recommends that ‘expert advice’ is sought in this case. Moreover, the foundational assumption that external air is of good quality is not always appropriate. This is acknowledged and advice for minimising the ingress of external pollution is given in Appendix D of ADF. Mitigation strategies for reducing traffic pollution include locating air intakes on the opposite side of the building from busy roads and reducing air intake during the peak traffic periods.

Thus some considerations beyond the constituents of indoor air are acknowledged by ADF, although they do not feed into the standard ventilation strategy. Whereas, the participants’ meanings associated with air and how they manipulated it incorporated thermal comfort, sounds, nature and interactions with others, as will become clear in the following sections.

The stated purposes of ventilation according to ADF begins to show a narrowness compared to the way the participants manipulate the air in their homes. The ADF strategy is built on the categorisation of outdoor air as more desirable than indoor air; and although deviations from this are acknowledged the challenge of addressing the conflicts raised by these conditions is addressed to a limited extent.

6.3.2 Ventilation strategy: three types of ventilation

Having established the purpose of ventilation, ADF sets out a ventilation strategy which comprises three types of ventilation:

- **Purge ventilation** should be available ‘throughout the building to aid removal of high concentrations of pollutants and water vapour released from occasional activities such as painting and decorating or accidental releases such as smoke from burnt food or spillage of water. Purge ventilation is intermittent, i.e. required only when such occasional activities occur’ (HMG, 2013b, p. 14).

- **Extract ventilation** should be provided in ‘rooms where most water vapour and/or pollutants are released, e.g. due to activities such as cooking, bathing or photocopying. This is to minimise their spread to the rest of the building.

This extract may be either intermittent or continuous.' (HMG, 2013b, p. 14).

- **Whole dwelling ventilation** is intended 'to provide fresh air to the building and to dilute and disperse residual water vapour and pollutants not dealt with by extract ventilation as well as removing water vapour and other pollutants which are released throughout the building (e.g. by building materials, furnishings, activities and the presence of occupants) (HMG, 2013b, p. 14).

This splits the different kinds of ventilation according to the expected frequency and locations of water vapour or pollutants from different sources. Purge ventilation is associated with removing water vapour pollutants in the event of one-off, high pollution events. Extract ventilation removes high loads of water vapour or pollutants which are expected to regularly occur in specific locations, the examples reference occupants' activities in the building. Finally whole dwelling ventilation is a continuous stream of ventilation to remove any remaining water vapour or pollutants and to provide 'fresh' air.

ADF's description of the ventilation systems give the technology and (indirectly) the occupant actions required to fulfil the intended operation of the system. These intended uses of the technologies can be translated as practical understandings that ADF assumes the occupants will carry out.

This ventilation strategy and the intended functioning of the ventilation system can be translated into the SPT framework so that the participants' practices can be compared to the ADF strategy. Taking purge ventilation through windows as an example: a window (technology) needs to be opened if there is smoke from burnt food (practical understanding) in order to remove airborne pollutants (meaning). The formal knowledge or rules element is so far lacking in this description. The Domestic Ventilation Compliance Guide states that end-users should be given an 'operation and maintenance manual [which] should contain specific instructions for the end user on how and when to use the ventilation system' HMG (2010e, p. 53). Such manuals appear to be the intended route for occupants to gain formal knowledge and rules regarding the operation of the ventilation systems in their homes.

The case study dwellings at CS2 had a continuous MEV system (system 3 in

ADF), the following section compares how ADF intends such dwellings to be ventilated with the participants' practices of manipulating the air. This is structured around the three types of ventilation just discussed, with the distinction between the types of ventilation emphasising the frequency with which the types of ventilation are expected to be required. There is potential for confusion between 'extract ventilation' as one of the types of ventilation in ADF just described, the continuous mechanical extract ventilation (MEV) system described in ADF (system 3) and the specific continuous mechanical extract ventilation (MEV) equipment installed in the case study flats. The latter two are always referred to as MEV to distinguish them from the type of ventilation, and continuous MEV is always suffixed with system where the whole ADF plan for this type of ventilation system is referred to.

6.4 Comparing ADF intended operation of the ventilation system and participant practices

The section above presented the ADF strategy for ventilation. This was translated into the Gram-Hanssen (2010a) SPT framework to set up a detailed comparison of the ADF ventilation strategy and intended operation of the ventilation system with the participants' practices related to manipulation of air in their homes. This section takes each type of ventilation from the ventilation strategy (whole dwelling, extract and purge) and compares the ADF expectation of this type of ventilation with the participants' practices at CS2. Instances where the participants deal with a pollutant or water vapour in a different manner than assumed by ADF are discussed in the section relating to the type of ventilation that the ADF strategy assumes will deal with that kind of pollutant. For example, use of the cooker hood is discussed in the extract ventilation section because cooking is a high pollution event which occurs in a specific location, even though the cooker hood in these flats is recirculating and therefore is not part of the planned ventilation strategy.

This section firstly discusses the **whole dwelling ventilation**: the ways ADF intends this to happen, as well as the parts of the practice of manipulating the air which are continuous and occur throughout the dwelling. Section 6.4.2 presents the results relating to **extract ventilation** - the ADF intentions for this and the aspects of the participants' practices of manipulating the air which were related to these intentions. This included parts of the practice of manipulating the air that were regularly carried out, associated with specific events, associated with other practices in the home and which were related to localised conditions within the dwelling. Section 6.4.3 discusses **purge ventilation** - ventilation for one off and extreme events. Components of the participants' practices related to manipulating the air which do not fall within the ADF ventilation strategy are then discussed in Section 6.4.4. These sections allow an overall discussion of the similarities and differences between ADF intentions and participant practices, this is given in Section 6.4.5.

6.4.1 Whole dwelling ventilation: continuous strategies

This section initially explains the intention for whole dwelling ventilation in the CS2 dwellings according to the description of continuous mechanical extract ventilation (MEV) systems in ADF. The implicit occupant actions (practical understandings) required for the system to function in the intended manner are highlighted. It then explores the meanings associated with whole dwelling ventilation given in ADF and the extent to which these meanings are part of the participants' practices. The ways in which the participants attend to these meanings through practical understandings and technologies are also discussed and the participants' interpretations of the ADF intended technologies are then presented.

6.4.1.1 ADF expectation of whole dwelling ventilation

According to ADF, the whole dwelling ventilation rate should be provided by a continuous flow rate through the continuous mechanical extract ventilation (MEV) and a minimum flow rate is specified. This means ADF intends the MEV to be continuously switched on, which requires the occupants to keep the MEV system switched on (a practical understanding). At CS2, the continuous MEV system could be switched on or off with an isolation switch in the utility cupboard, see Figure 6.1. It is worth noting that the measured ventilation rates indicated that despite

Figure 6.1: Continuous mechanical ventilation isolation switch (top right) amongst other isolation switches in the utility cupboard at CS2.

MEV flow rates higher than required by ADF the whole dwelling ventilation rates remained low (see Section 5.5.4), so the installed systems at CS2 were usually not able to deliver sufficient ventilation rates for whole dwelling ventilation.

ADF intends air inlets to be provided by trickle vents (background ventilators) and infiltration through the fabric for continuous MEV systems. Trickle vents 'are intended to be normally left open in occupied rooms in dwellings' (HMG, 2013b, p. 15), although they 'often incorporate a simple flap that allows users to shut off the ventilation – depending on external weather conditions' (HMG, 2013b, p. 15). Trickle vents were routed through the top of window frames and could be hinged open, see Figure 6.2. Keeping the trickle vents open is another practical understanding.

The whole dwelling ventilation rate is meant 'to provide fresh air to the building and to dilute and disperse residual water vapour and pollutants not dealt with by extract ventilation as well as removing water vapour and other pollutants which are released throughout the building' (HMG, 2013b, p. 14). These can be interpreted as the meanings element of a practice, having fresh air and having air free from pollutants; these are discussed below.

(a) Closed trickle vent

(b) Open trickle vent

Figure 6.2: Open and closed trickle vents at the top of a window frame at CS2.

6.4.1.2 Providing fresh air

Several of the participants had a sense that air in the flat should be fresh and in order to achieve this the air should be kept moving:

BRANDON I just like the idea of fresher air in the apartment, I always like the air circulating, because it's a small place, you need to kind of keep it moving I think.

CAL I like it when it's fresh, and by fresh I mean just like to feel that it's, you know, it's been circulated, it's like and it's not a bit stuffy.

The opposite was also mentioned:

ALICE [Stale] air has just been sort of stagnant and not moving and so it means that [...] minor smells [from] food residue or stale water in the sinks [are] just sat there.

Here the negative connotations of stale or stuffy air are somewhat connected to a sense of the air being unclean, whereas the freshness of air is pleasant and associated with cleanliness. This will be explored in the following section with reference to the interpretation of particular smells in the home. Part of the participants' practices of manipulating the air included a meaning of maintaining fresh air in their homes, and this was associated with societal expectations of cleanliness.

The primary practical understanding of how to achieve fresh air was to use the windows:

BRANDON I used to just tip them, maybe not all of them, maybe just one of them, every time [I left the flat] just to circulate the air.

Alice also finds that if the windows are closed for several hours then the flat becomes stuffy and windows need to be opened. She thinks that the absence of windows contributes to increased stuffiness in the bathroom.

In all cases, opening the window is referenced as the only action to take for alleviating stuffiness. However, the ADF intention is that the continuous MEV drawing air in through the trickle vents and unplanned leakage pathways should provide sufficient fresh air, Cal believed that this system should help to alleviate some amount of stuffiness:

CAL I can sometimes feel like when I come home that maybe it's a bit stuffy, like maybe because there I wasn't in, and that's why I was asking, sometimes I was wondering if the ventilation works properly so I kind of was opening the window just to freshen up a bit at times
(*Later on*)

CAL I mean I just, what I believe is just that [the continuous MEV] takes the air just in general circulates the air in the flat

Cal thinks that the continuous MEV should circulate air in the flat, providing fresh rather than stuffy air, the stuffiness of the flat could be an indication that it is not working properly. In order to compensate for this and provide sufficient fresh air his practical understanding is that the windows need to be opened.

Cal is aware that the MEV system makes a noise because when he goes on holiday he switches the ventilation system off (along with other appliances including the fridge) and when he comes back he switches the MEV system back on and hears the system as it starts. This indicates that the system does something:

CAL [The noise of the continuous MEV is] very very subtle which is fine, but also like, are they doing any work, are they working properly or not? But again, I wouldn't equate just if it's noisy it means it works.

Although the noise indicates that the system switches on, this is not enough to indicate that the system works properly since the air was perceived to be stuffy. Despite this, Cal has no recourse to find out whether the system is working well and is keen to see the results of the fan flow measurements taken following the interview. This highlights the limited practical understandings related to the continuous MEV; Cal was keen to see a measure of the MEV's performance as he found it difficult to interpret directly.

Furthermore, two of the participants discuss the ventilation system in their offices and indicate that the air they provide might not be perceived as sufficiently fresh:

CAL Having only the air conditioning or the ventilation bringing fresh air, it felt a bit artificial [...] it'd be nice to just open the window and have kind of fresh air, instead of being something just ventilated through the yeah tubes or whatever, the system yeah.

AARON All of the windows are sealed so you can't open any of them, and the air is circulated and its like it's really [...] awful when they're recycling the air and it feels sort of really stagnant, whereas like having the windows open is a lot nicer.

The air from their office ventilation systems is interpreted as unnatural and in some sense less fresh than air directly from outdoors. This further points to the participants' having the practical understanding that adequate fresh air is obtained through open windows, in contrast with ADF's intention that it will be provided by the continuous MEV drawing air through the trickle vents and unplanned leakage pathways.

6.4.1.3 Dilution of pollutants produced throughout the dwelling

ADF includes odour as a pollutant which should be dealt with by the ventilation system. The interviews revealed that smells in the home were significant to the participants. A particularly striking example was discussed by Alice and Aaron with regards to their dog; Alfie:

ALICE I am very conscious of the fact that we have a pet and you know, often as the pet owner you don't recognise that you might in fact be a very smelly person, and like I think it's much more telling for other people coming into the flat.

AARON Oh, yeah, like, we won't be offended, does our house smell like dog?

Aaron and Alice were clearly keen that their home did not 'smell like dog' as this was felt to be an inappropriate smell in the home. This meaning informed some of their practical understandings of manipulating the air in their home. A similar sentiment relating to the smell of pets was echoed by Darren:

DARREN If you're used to somewhere that seems relatively sterile and stuff like that, if you go into someone's place and they've got [...] a dog or something else, you can immediately tell, ooof, oof there's a whiff! (*laughs*)

This reveals that particular smells are especially socially significant, for Alice in particular the idea that guests might notice the smell of the dog is distressing:

ALICE when I leave the flat I open a window and turn [a plug-in air freshener] on, and then when I come back in the flat, because I find it's quite strong smelling and I don't really like it, but as I said, I'm conscious of having a dog, so especially like if other people are coming here I would like put the plug in on so that hopefully it doesn't smell awful.

Hauge (2013) discusses the social judgements related to smells in the home and the importance of conveying the 'correct' image to others who might visit the home through the smells present in the home. This concern over the judgement by others of smells in the home is particularly strong for Alice.

Moreover, Darren's use of the word 'sterile' points to an association between the smell of the home and the perceived cleanliness, this was also raised in relation to his sister's flat:

DARREN She has a bunch of room mates who are just like really lazy about cleaning up anything, so the whole place always smells. [...] I mean she's [...] like, 'I want to open the windows so I don't feel like I'm suffocating' (*laughs*)

Here, the sensing of smells is bound up with an assessment of the character of the people Darren's sister lives with. Wakefield-Rann et al. (2018) discuss modern home cleaning practices and how people have become sensitized to specific smells, sights and sensations as indicators of 'uncleanliness', 'germs' and other micro-organisms. Shove (2003) wrote comprehensively about the social significance of cleanliness, and how this has been bound up with notions of propriety and morality. In these examples the participants show that the smells in air can be a source of judgement or fear of judgement especially where these smells are associated with interpretations of cleanliness. The participants wanted to avoid such smells where possible.

The practical understandings discussed in the previous section relating to fresh air referred to the use of windows, but further practical understandings were referenced by Darren and Alice in the quotes above. Darren indicates that the source of the smells in his sister's flat would be removed by 'cleaning up'. From a technical perspective this could be translated as a practical understanding of source control. However, cleaning products themselves can be significant sources of indoor air pollutants, so there could be a tension between the participant's practical understanding of source control and a technical perspective in which 'cleaning up' potentially involves one set of pollutants being replaced by others.

Additionally, Alice shows that scented products were used to mask unwanted smells and introduce desirable smells. For Alice, using scented products is one of the things she can do to manage the smell of the dog. She tolerates an air freshener that she personally does not like in order to give a scent in the home that she feels is more socially acceptable.

This use of intentionally scented products is at odds with the ADF conception, in which 'odours' are removed via ventilation. Air fresheners contain various pollutants including VOCs (Steinemann, 2017), and therefore from an ADF perspective the introduction of scented products constitutes the introduction of pollutants. This is a striking contrast in the perspectives between ADF and the participants' practices. Alice perceives the introduction of the air freshener as a way to remove the problem of the smell of the dog and provide more socially acceptable air, whereas for ADF an additional pollutant has been introduced in the form of the air freshener. Alice's use of the air freshener is intermittent, but this is partly because she does not personally like the scent of the air freshener.

Alice disliked the air freshener but felt that it was necessary because of the significant smell from the dog, whereas other participants had stronger feelings about air fresheners:

BRANDON I don't like the smell of those fake air fresheners, like the Christmas tree things, they don't add to the air quality, they make you a bit coughy don't they?

Although Brandon used several scented products, he is specific about which ones he likes and dislikes. Darren echoed a similar sentiment, with no tolerance for any air fresheners:

DARREN I really am not a fan of any like incense or any, any fresheners, they always smell a bit off to me, so yeah I don't like anything really in the air.

These quotes indicate that Darren and Brandon have some direct experience of detriment to health associated with scented products. Although air fresheners are likely to be sources of indoor pollutants (Steinemann, 2017), the participants had no formal knowledge and had received no advice regarding their use in the home. In this case Brandon only perceived a problem when particular products were 'coughy'. Thus keeping the air free of pollutants from scented products extended as far as those which induce a direct physical reaction. Brandon and Darren choose not to use products that they feel are detrimental in their homes, and in this way they control the sources of pollution.

This section has shown how the participants were keen to dilute certain kinds of pollutants, but their their interpretation of what a pollutant is differs from ADF's.

6.4.1.4 Residual pollutants not dealt with by extract ventilation

The final purpose of whole dwelling ventilation according to ADF was to remove residual water vapour and pollutants not dealt with by the extract ventilation. This presented a challenge in aligning the discussion of the participants' practices with the ADF framework since this purpose could be interpreted as a 'catch-all' for anything related to the pollutants ADF intends to be removed primarily by extract ventilation but the participants dealt with by different means. Following the rationale that the overall intention of the whole dwelling ventilation was to provide continuous, low level ventilation throughout the building, and of extract ventilation was to provide higher levels of ventilation in the specific locations required (often intermittently) all the elements of the participants' practices that related to manipulating the air in specific locations are discussed in the extract ventilation section. The interviews revealed nothing significant in the participants' practices of manipulating the air which related to affecting conditions in the whole flat to deal with residual pollutants from specific locations.

The results so far have shown that technologies the participants used to provide the whole dwelling ventilation purposes set out in ADF did not include the technologies assumed by ADF. The following section discusses these technologies and the participants' use of them.

6.4.1.5 What about the intended technologies?

Windows and air fresheners were the primary technologies involved in the continuous aspects of the participants' practices related to manipulating the air which have been discussed so far. This is in contrast with the ADF intention that continuous ventilation be driven by the continuous MEV drawing air through trickle vents and other unplanned infiltration paths. This section explores these intended technologies and the extent to which they were embedded in the participant's practices.

6.4.1.5.1 Continuous mechanical extract ventilation As discussed above, Cal had the impression that the continuous MEV was supposed to permanently circulate the air and that this should provide fresh as opposed to stuffy air, whilst the other participants had variable awareness of the system. Brandon was unaware of the presence of the system:

JESSICA I wondered as well if you could tell me if there's a ventilation system in the flat?

BRANDON Yes. There is if you lift up the hood of the cooking

(*Further discussion of the cooker hood*)

JESSICA Yeah, ok and is there any other kind of fans or. . . ?

BRANDON No, I mean I'm sure you can buy them but I didn't.

(*Interview continues, then towards the end of the interview*)

JESSICA In the kitchen as well next to the smoke alarm there's like a round sort of terminal thing.. do you, I don't know if you ever noticed that?

BRANDON No, I can't remember, was it, was that not the fire alarm?

(*Discussion of the terminals*)

JESSICA So in the utility cupboard, I don't know if you know about there's a switch for the fan?

BRANDON Yes I do, I remember that.

JESSICA Ok cool, did you did you switch that off at some point or..?

BRANDON I don't think I ever touched it, was it on or off?

The isolation switch in the utility cupboard at Flat B was off at the time of interviewing Bridget, who had also never touched the switch. Bridget did recognise the terminals on the ceiling as being part of a ventilation system as her family home had something similar. Although the continuous MEV is designed work in the background without input from the occupants, for Brandon the system is so much in the background that he has no notion that anything is amiss while the ventilation system is switched off. The rest of the flats did have the system switched on, although in Flat A the isolation switch for the whole system was mistaken as the switch for the utility cupboard extract since the switch is located in the utility cupboard.

Darren explained why he has paid little attention to the continuous MEV system:

DARREN It's one of those things, like, you never look at how your plumbing system works until your taps don't work.

In a previous flat Darren was much more conscious of needing to take actions to obtain and maintain air with appropriate qualities. He found that his previous flat was often too hot, too stuffy, or that cooking smells lingered after cooking; these qualities indicated to him that the air needed attention. However, he is in general happy with the air in his present flat and does not find that the air has any of these qualities, nothing indicates to him that he needs to take any actions to manipulate the air.

None of the participants refer to any formal knowledge or rules regarding the continuous MEV. The continuous MEV system is designed to work without intervention from the occupants. The participants have no doings associated with the system, no rules or formal knowledge and sometimes vague interpretations of what the system is doing.

6.4.1.5.2 Trickle vents ADF intends that trickle vents are almost always open, with some expectation of closure in some weather conditions. However, on all occasions that the flats were visited by the author all trickle vents were closed. The participants had differing awareness of the function of trickle vents, as demonstrated when Aaron mentions having opened the trickle vents:

ALICE Oh! You can do stuff to them!?

AARON Yeah. . . you just flick them open.

ALICE Oh! Well I didn't know that, what does that do?

AARON Lets a small amount of air in.

Bridget was similarly unaware of the presence of the trickle vents, and Darren had never noticed them in Flat D, but did keep them open all the time in his previous flat:

DARREN My previous place I had [the trickle vents] open the whole time because letting heat out just passively and just any sort of airflow at all was quite important. Because it was only facing one way and also, the [front] door was like, to the rest of the block of flats was super airtight and things like that, so there was no airflow at all

Darren left the trickle vents in his previous flat permanently open. However, in his current flat he felt that neither heat nor smells got trapped inside, and as a result, although he has the practical understanding that trickle vents can provide additional airflow, this was not wanted. When the trickle vents in Flat D were brought to his attention during the interview he immediately checked all were closed as he felt the flat to be cold. This highlights how the practice of manipulating the air is linked with thermal comfort.

Brandon was also aware of the presence and function of the trickle vents but never touches them for a different reason:

> BRANDON because the windows don't open that much at all, it's probably the same effect really, [as] just opening the window.

For Brandon, any function that the trickle vents might have can be carried out just as well by the windows, so nothing signifies to Brandon that the trickle vents should be opened.

Only Cal and Aaron have occasionally used the trickle vents in these flats, both on occasions when they were not present and did not want to leave windows open:

> AARON (*Talking to Alice*) [It] drives me up the wall when you leave the window open when we go away because I'm always convinced someone's going to break in and steal everything. So I closed the windows [after you went] and I opened the air vents.

Opening the trickle vents was felt to be a safer alternative for getting fresh air into the flat while Aaron and Alice were on holiday. Aaron and Alice's discussion at this stage in the interview revealed their different priorities around security and freshness of air and could point to the possibility for the trickle vents to mediate this difference. Although, Aaron says earlier in the interview:

> AARON [when we've gone on holiday and] we have closed the windows, or when I've gone after you've gone and I've closed the windows then it's quite stuffy [when we come home].

Unfortunately, it is unclear whether Aaron found the air stuffy on an occasion on which he had left the trickle vents open or not and thus whether or not the trickle vents were perceived to adequately alleviate or prevent stuffiness.

Similarly, Cal had opened the trickle vents on a few occasions when he wanted some airflow without leaving the windows open while the flat was unoccupied, for example when drying clothes. In this case, Cal had a practical understanding that drying of clothes meant that additional ventilation was necessary and that trickle vents could provide this without compromising security.

Although both Cal and Aaron have occasionally used the trickle vents, in neither case was the use of trickle vents a routinised action nor something that was consistently done when other activities were carried out. Although the participants who were aware of the vents understood their potential for providing outdoor air, open vents was not something that they felt should be the default, nor had opening the vents become a common action taken to manipulate the air in the flats. While ADF intends that trickle vents will be usually open and only closed in particularly poor weather, the participants use them in almost the opposite way, they are usually closed and only opened in special circumstances. In no instances were the trickle vents a significant part of the participants' practices, only something occasionally and sporadically used.

6.4.1.5.3 Infiltration The intention according to ADF is that infiltration through unintended cracks in the building fabric provide part of the intake air.

Darren and Cal both noticed movement of air from the front door undercut. These undercuts are not required according to ADF, while undercuts beneath internal doors are. Darren had noticed the front door undercut in winter:

DARREN Normally the air in the corridor is actually a little warmer in the winter. Sure warming the feet!

While Darren perceives that the undercut positively influences the temperature in the flat, Cal has mixed feelings:

CAL Obviously in the summer it's perfect because it's nice it cools it down, but in the winter I believe that might make it a bit cooler in terms of temperature, instead of keeping the temperature warm.

In both cases, this movement of air is only associated with maintaining the right temperature in the flat, rather than with any of the other meanings associated with manipulating the air.

6.4.1.5.4 Internal door undercuts Undercuts are required beneath all internal doors and are intended to ensure that air circulates around the dwelling even when doors are closed. In ADF undercuts are not specifically associated with any particular type of ventilation, however as they relate to ensuring that air flows around the entirety of the building, they are discussed here.

The undercuts of internal doors were never mentioned until prompted and the participants had given them little thought. Alice recalled using a draft excluder in a previous home where the undercut caused a noticeable flow of air, again air movement was associated with thermal comfort, but no other aspects of manipulating the air. As noted in Section 5.5, the door closing data indicated that the participants rarely closed the doors in these flats.

6.4.1.6 Continuous ventilation summary

The ADF purposes of whole dwelling ventilation have been shown to be broadly associated with some of the meanings the participants have for manipulating the air in their homes. Akin to ADF, the participants clearly had meanings associated with fresh air and dilution of some pollutants. However, the participants' perception of airborne pollutants were dominated by unpleasant scents, or pollutants that had a tangible and immediate effect on their health (e.g. Brandon's 'coughy' air freshener). ADF includes 'odour' as a pollutant, but also considers unscented or pleasantly scented compounds to be pollutants if they pose risks to health; for example the VOCs in air fresheners. The participants had no formal knowledge or rules relating to these potentially harmful indoor air pollutants.

Moreover, generally the participants did not use the technologies intended in ADF to address these goals or meanings. The participants' practical understandings related to whole dwelling ventilation involved using mostly windows or air fresheners. The participants had no formal knowledge or rules related to keeping the trickle vents open or the MEV on.

This section has discussed whole dwelling ventilation - continual ventilation for constant provision of outdoor air. The next section discusses extract ventilation.

6.4.2 Extract ventilation: localised ventilation for regular or continuous sources

This section compares the ADF intention with the participants' practices in terms of localised regular or continuous sources of pollution, in ADF these are dealt with by extract ventilation. The first part of this section describes how extract ventilation should be provided in flats with a continuous MEV system according to ADF. Subsequently, the particular case of cooking as a regular event is discussed in Section 6.4.2.2 because this was a particularly clear example highlighting the differences between ADF's intention and the participants' practices. Further insights relating to regular events are discussed in Section 6.4.2.3 and continuous localised sources of pollution are discussed in Section 6.4.2.4. Again, it will be seen that the intended technologies are involved only to a limited extent in the participants' practices, so Section 6.4.2.5 will discuss use of the intended technologies.

6.4.2.1 ADF expectation of extract ventilation

According to the ADF ventilation strategy, extract ventilation should be used in rooms where the most pollutants or water vapour are produced to prevent their spread to the rest of the building. For continuous MEV systems this should be provided by a high flow rate through the MEV (greater than the flow rate which provides the whole dwelling ventilation discussed in the previous section). Preventing the spread of water vapour or pollutants to other parts of the dwelling can be translated as a meaning in the SPT framework. ADF gives cooking, bathing and photocopying as examples of activities which would require extract ventilation.

The ventilation systems outlined in ADF presuppose which rooms will have the greatest need by requiring that these rooms have provisions for extract ventilation: kitchens, bathrooms and utility rooms. ADF states that extract ventilation may be intermittent or continuous. However, the switch between low and high flow rates is permitted to be automatically triggered by sensors. Such automatic switches further presuppose which activities will take place and result in high water vapour or pollution loads; they also remove the possibility for continuous extract ventilation unless the specific conditions that trigger the switch are continuously met (for example, if humidity is continuously high in a dwelling with a humidity-controlled switch). Thus, ventilation systems complying with ADF guidance are not necessarily able to deal with all kinds of continuous, localised, high concentrations of pollutants, despite the ventilation strategy indicating that such sources should be dealt with by extract ventilation. Nonetheless, the interview data relating to participants dealing with high pollution loads from continuous sources are presented here, as the ventilation strategy indicates that these should be dealt with by extract ventilation.

The plans for the ventilation system at CS2, provided by the developer, indicated that the high flow rate would be automatically triggered by humidity sensors. However, ADF states that the boost rate should not be controlled by a humidity sensor in sanitary accommodation as odour is the main pollutant, since the bathrooms at CS2 contained a toilet and a shower these plans did not comply with the ADF design. The planned automatic control of the high flow rate meant that there were no actions that the participants could take to increase the ventilation rate using the planned continuous MEV system. There were also no windows in the bathrooms at CS2.

Moreover, in contrast to the planned system, no evidence of a boost flow rate was found at CS2. The ventilation system continuously provided a constant flow rate, which was often higher than required for the whole dwelling extract rate, but usually lower than required for the high flow rate, see Section 3.6.3. At CS2 the lack of observed boost functionality, as well as the measured ventilation rates indicated that despite the high MEV flow rates whole dwelling ventilation rates remained low (see Section 5.5.4), so the installed system was not able to deliver sufficient ventilation rates for extract ventilation.

Additionally, it is worth noting that cooker hoods are not required according to ADF for continuous MEV systems, although they can be used to provide extract ventilation in the kitchen. At CS2, extract ventilation in the kitchen was provided by the central MEV system. The cooker hoods at CS2 were recirculating hoods: they filter some of the smells of cooking but they are not part of the planned ventilation system. Nonetheless, the cooker hoods were an important technology the participants used to control cooking smells, as discussed in the following section.

6.4.2.2 Ventilation and cooking

The participants clearly had meanings associated with the amount and duration of cooking smells:

CAL If I fry [...] garlic and onion and then it's like ok, it's a nice smell but I don't want to have it all night!

While the smells of cooking are pleasant during the act of preparing food, there is a limited period of time for which this is appropriate. This is similar to the intention of extract ventilation in ADF, in which it is expected that some activities will be associated with increased pollution, but that the effect of this should be limited.

Moreover, for some participants the location of the smell was important. Flat B was a studio flat, having only a door for the bathroom, but Brandon had installed a folding divider between the kitchen-living room area and bedroom area and explained why he would prefer to have a separate bedroom:

BRANDON I guess just the smells of the cooking. Um yeah I mean it's yeah. Just to keep that a bit more separate.

This reveals a meaning of having appropriate smells in appropriate locations, and the practical understanding that a separate room with a door would enable smells to be confined to appropriate areas of the flat. The meaning here is similar to ADF's intention that the spread of pollutants around the dwelling should be limited, although the technology and practical understanding is different.

Practical understandings for managing appropriate amounts of cooking smells included opening windows. Windows closest to the kitchen were often opened to remove cooking smells, again mirroring the spatial aspect of extract ventilation in ADF. Cal found that if cooking smells travelled into the bedroom area then it was necessary to open the bedroom window as well, again indicating a sensitivity of the location of smells within the dwelling. However, windows were sometimes closed despite cooking smells:

> CAL [If it's] cold enough in the sense that I'm freezing, I need to close the window regardless how it is

Here the temperature of the outdoor air influences the amount of cooking smells the participant is willing to tolerate, and changes the options available for manipulating the air.

Alice, Aaron, Brandon and Cal shared the practical understanding that the cooker hood is usually or always used when cooking:

> BRANDON Just to keep it fresh I guess and you can see the steam going up it and all the smoke going up it if you need to.

Removing the cooking smells contributes to keeping the air fresh (a meaning that was discussed in the previous section), and the visualisation of the smoke and steam help to indicate what the cooker hood is doing. Brandon believes that the cooker hood must be on in order for the hob to switch on (although Bridget who rents Brandon's flat does not use the cooker hood), despite this Brandon says he would use the cooker hood regardless of whether this was enforced by the technology.

Although these participants perceive the cooker hood to help contribute to maintaining appropriate smells and freshness in the flat it does have some drawbacks:

> CAL It's a bit annoying, I think maybe it has three kind of stages but the last one is the most annoying one, but it's the most effective one as well. So... yeah, this is how I use it, usually just the first or third speed, either just depending what I cook.

The noise of the system is a disadvantage but the hood is nonetheless perceived to be necessary. The speed setting means that an appropriate amount of filtration can be chosen as appropriate for the smells being generated.

Bridget and Darren on the other hand do not use the cooker hood, Bridget explains why she has stopped using it:

BRIDGET I am afraid about the smell so I just put the (*motioning towards the hood*)

JESSICA Yeah the hood, we call it a hood!

BRIDGET Yeah the hood, and so [I used it for] two weeks then I cook all the day I find that it's not a smell bad [sic] so I never use it again.

Bridget clearly shares the meaning that too much cooking smell is inappropriate and she wants to avoid this. However, she finds that without using the cooker hood the smell in her flat remains appropriate. Darren's account is similar:

JESSICA Have you used them ever in, in previous places have you ever used the extract?

DARREN Yeah, yeah, like everywhere before. Here, just very easily fall into a habit of just not doing it, because it doesn't seem to have any negative consequences, so.

This shows how Bridget and Darren's practices of manipulating the air have evolved as they inhabit different homes, they had updated their practical understandings upon finding that the air remained acceptable in terms of cooking smells without using the cooking hood. This illustrates that the practice is malleable and partly informed by a reaction to the conditions that they perceive in their home environment.

Although neither Darren nor Bridget used the cooker hood, they were well aware of signs that would indicate that they need to use it. They know that the cooker hood could be used as part of their strategy to control the cooking smells in their home if they found that these smells were inappropriately strong. In this sense the cooker hood has been interpreted in a very similar way by all participants. Similarly, there were common practical understandings around using windows to remove cooking smells and internal doors to limit their spread. However, only Darren suggested that the continuous MEV system might be having an effect on cooking smells:

DARREN there's not fans, there's these (*Darren points to the terminal on the kitchen ceiling*), which I presume are taking some of the smells away and stuff like that

The meanings associated with dealing with cooking smells are quite similar to ADF's purpose for extract ventilation, the participants were keen to remove the smells (pollution) associated with cooking and to limit their spread throughout the flat. However, the lack of an increased flow rate from the continuous MEV means that the system as installed does not match the ADF intention, so the route through which high pollutant loads are dissipated cannot match the ADF intention. Extract ventilation in these flats happens through occupants actions, in direct contrast with the planned automatic system. The technologies used and practical understandings in the participants' practices are inevitably wholly different to those planned in ADF for extract ventilation.

6.4.2.3 Other regular events involving regular ventilation

Apart from cooking, there were several other practices that the participants associated with actions which affect the indoor air. In particular, the participants often took specific actions to manipulate the air for sleeping or after sleeping.

> CAL I open [the windows] in the mornings also in the winter, so also again, just to kind of, you know after a night just to kind of get some fresh air.

Opening windows is part of Cal's morning routine, part of the structure of the day, and refreshes the air after a night of sleep. The meaning of freshness here is similar to that discussed in the previous whole dwelling ventilation section. In the ADF strategy, maintaining appropriate freshness of the air should be achieved by the continuous ventilation from the MEV system. However, for Cal this is not sufficient and as a result additional ventilation after sleeping is required in winter to give the desired fresh quality in the air. In warmer months, this is sometimes achieved by keeping windows open at night:

> CAL It has its pros and cons because if the window is closed there's no noise and it's pleasant, but then also it feels, you know it gets a bit too hot and you know in a way, stuffy, because it's hot outside, but if I leave it open it's nice that it's fresh air but then also means the noise comes in.

Again, Cal shows that fresh air is desirable, and he has a practical understanding that opening windows can give 'fresh' as opposed to 'stuffy' air. However, additional considerations of noise and thermal comfort are important in creating the right environment for sleeping. Similarly, for Alice sleeping with open windows is preferable:

ALICE [At night] I would leave one in [the living room] open, because the noise would be too much in the bedroom if we had the window open at night [. . .] I would, I would rather sleep with the window open, it's literally just the noise [. . .] I prefer sleeping with like moving air I think, it's just more comfortable, I think.

Alice likes to feel that the air is circulating while sleeping, and her practical understanding is that opening windows is the way to achieve this. Again, this contrasts with the ADF strategy, in which the continuous MEV system should provide sufficient continuous circulation of air. Aaron and Alice's flat was at the back of the building and was close to a train line which carried freight overnight, closing the bedroom window meant that this noise was blocked out, although open windows in the bedroom would have been preferred. Noise was also a consideration for Bridget:

BRIDGET I let like this [tipped open] when I go out to [University] and I just close when I go to sleep. . . not to hear some police, or but yeah I let, in September and October I let the windows open most of the time and after I close it.

While Bridget likes to have windows open during the day if it's warm enough, windows are always closed at night to keep out noises which would disturb her sleep. Pickering and Rice (2017) argue that in the same as way as Mary Douglas evokes that 'dirt is matter out of place', we can interpret noise as sound out of place. By doing so, the idea that noise is a form of pollution is clarified, and the social significance of noise becomes clearer.

As well as noise, the participants used windows to affect the thermal conditions as noted above. Darren relates his overnight bedroom door closure to having an excessively warm duvet as a child:

DARREN So I'd always have the window open and try and make it cold in my room, and I think [my parents] started shutting the door, just like keep the cold in there if that's what he wants.

In Darren's childhood, the bedroom window was being used to provide an appropriate temperature for Darren while sleeping under his very warm duvet, and the bedroom door was being used to facilitate different temperatures preferred by other members of the household. For Darren, closing the bedroom door has persisted into adulthood (although he very rarely opened the windows for security reasons, see Section 6.4.3).

Several other regular events apart from sleeping were discussed with reference to affecting the conditions. For example, Bridget explained why she leaves the bathroom door open while showering:

BRIDGET [I] hate the feeling when I leave the bathroom and I'm cold so I prefer let the door open and the air can change, yeah and not be cold when I go out.

In this case, Bridget found that the heat from the shower warmed up the bathroom, and she disliked feeling the relative coolness when she opened the bathroom door after a shower. The doors were involved with manipulating the air to obtain the right temperature at the moment of leaving the bathroom. In other instances bathroom doors were opened to dissipate humidity immediately following a shower, this directly contrasts with ADF's purpose for extract ventilation which is to prevent the spread of pollutants and moisture.

The use of doors described by Bridget and Darren could be similar to Royston's (2014) concept of heat-out-of-place and heat-out-of-time, which is the idea that occupants manipulate heat flows using a range of skilful interactions in order to obtain the right temperature in the right space at the right time and reduce wastage of heat. By using the doors, the participants are controlling the location and flow of heat around the building, so that they obtain and maintain conditions they find thermally comfortable in particular spaces and at particular times.

The use of doors also had social implications which were not framed in terms of controlling environmental conditions. For example, Aaron and Alice discuss closing doors at home:

JESSICA Are there ever circumstances in which you close the living room door, this one?

AARON Blazing row! (*All laugh*)

(*Later on*)

ALICE I don't really like the feeling of being in a room with the doors closed.

(*Later on*)

ALICE Yeah I suppose in my life, I've only really closed doors for privacy as opposed to any kind of temperature or air reason, it's always only been yeah, that would be the only reason I would close a door.

Having the internal doors open seems to be part of creating the right feeling of being at home for Alice, and the use of doors is related to the social relationships between the occupants.

Closing bedrooms doors for privacy when living with other people was a common action for all of the participants. Sometimes the opposite case arose, where doors were opened specifically for open communication. Cal had bedroom doors open during the day when he lived with a friend:

CAL I would leave the door open from my door just for, you know, transparency. And also, just, like I would leave it open because it was nice to have interaction with other, because I living with another only one mate in that place, so it was nice to just have the door open and just maybe sometimes chatting or so on.

Open doors were part of the way Cal communicated and maintained his social relations with his flatmate. Although such uses of the internal doors are couched in terms of privacy or transparency, they could still relate to controlling the environmental conditions in particular locations within the home; part of the way privacy is assured is through blocking light transmission and reducing sound transmission through a closed door.

Sometimes, the reasons for door use were not clear, for example Brandon said that he liked to sleep with a closed bedroom door:

BRANDON I don't know it's almost like a thing, I have to have the bedroom door firmly closed. I don't know why, but...

For Brandon, closing the bedroom door is an important part of setting up the right environment for sleeping, although he is not conscious of a reason for this. Similar to Alice's preference for open doors referenced above, the position of the door for these participants is part of creating the right conditions at home.

This section has shown how the practice of manipulating the air can be understood as dispersed (see Section 6.2): involving small scale actions which take place in various contexts and have different meanings when performed in different circumstances. It was shown to be involved with integrative practices of showering, cooking or getting ready to sleep, as well as other dispersed practices such as thermal comfort at home. Manipulating the air was related to a broad range of conditions including smells, noise, privacy and thermal comfort. Although some of these are briefly mentioned in ADF, there is no detailed consideration of how this might affect the ventilation in the dwelling, particularly as relates to extract ventilation as opposed to purge ventilation.

The intermittent manipulation of air related to specific activities were discussed above, while the following section discusses continuous sources of pollution.

6.4.2.4 Continuous and localised pollution sources

As discussed in Section 6.4.2.1 the ADF ventilation strategy states that extract ventilation may be continuous as well as intermittent. However, the ventilation system had no planned route by which occupants could remove continuous, localised, high concentrations of water vapour or pollutants, especially where these occurred in unexpected locations or were not associated with the conditions which would trigger an automatic switch from background to extract ventilation. Such situations may be challenging to factor into the design of a ventilation system, but they raise an important consideration regarding contingency in planned ventilation systems. Damp and mould growth represent a potentially significant and continuous source of pollution in the home. Alice referred back to a student house with extensive mould on the walls:

ALICE I had an entirely black wall, so I feel like we've been lucky since then!

JESSICA How was that, living with that?

ALICE It was horrible, I had like, I definitely feel like I had more kind of colds than I would normally have in a year, like it was yeah, really quite unpleasant, and it was, you could smell it as well.

The smell of the mould was unpleasant, and the black appearance of the mould indicated a lack of cleanliness which was undesirable in the home, as discussed in the whole house ventilation section regarding provision of ‘fresh’ air.

Darren recalled a similar situation in a University hall of residence, in which a pipe had burst in the corridor, but the facilities management decided to wait until the students moved out before fixing the underlying problem:

DARREN The smell, oh yeah, definitely. Horrendous.

JESSICA Mmm was there anything you would try and do to sort of limit it in your room, or..?

DARREN Well, my room was like really close to it, so like, if you can imagine, there’s not much, not great quality doors or anything like that, and the window [...] the only bit you could open was like that (*gestures about 30 cm x 30 cm*). Yeah, urgh.

Although windows were used to mitigate the effect of these sources, ventilation alone is clearly inadequate to deal with this kind of problem, and advice to ventilate was sometimes met with disdain. Aaron and Alice discussed being told by a previous landlord to open windows in response to damp:

AARON He was like ‘oh you’ve got damp, just open the windows’.

ALICE I feel like most landlords, like if you report damp they’ll say, open the window, as if that’s some kind of...

AARON You could tell that guy your house was on fire and that guy would have told you to open the fucking windows.

These issues raise two points. Firstly, these problems with mould and damp highlight how the planned ventilation system is potentially unable to deal with continuous high concentrations of pollutants, unless these sources trigger the switch to automatic extract ventilation. A particularly problematic issue is raised by humidity-based automatic control of extract ventilation since the presence of cold spots on walls increases humidity locally, which may therefore not be detected by the ventilation system, this could lead to mould growth in some circumstances. Additionally, the location of unexpected continuous sources of pollution could problematic. Extract ventilation is provided in specific rooms according to the ADF design; if there was mould growth in a different room it would be unsatisfactory to use extract ventilation in another room as this would draw airborne pollutants through the dwelling. Moreover, mould would be a continuous source of pollution until it had been removed and any underlying issues (including inadequate ventilation) had been resolved.

Secondly, Aaron and Alice's instruction from the landlord to open the windows in response to damp was not well-received. The comparison between ADF and the participants' practices has so far revealed very little of the formal knowledge and rules element of the SPT framework. Landlords could be a source of formal knowledge and rules, but the quote above indicates that their advice must be interpreted as appropriate by the tenants.

The mould and damp were interpreted as unpleasant, so the participants were inclined to take actions to deal with them. However, significant sources of pollution may also be interpreted as pleasant, Brandon explained how he liked to burn scented candles:

BRANDON Pretty much every time I was in the flat. I'd walk in, light them.

(*Later on*)

BRANDON It's the ambience, the relaxation of them, the smell of them. I like the musky smoky ones.

Bridget referred to similar reasons for liking to burn candles. Lighting the candles is one of Brandon and Bridget's practical understandings of relaxing and creating the right atmosphere for home. Brandon's use of the candles was very frequent, something he did almost every time he arrived in the flat.

The candles represent a significant source of pollution which is almost always present when Brandon is at home, although this is not something he is aware of. Similar to the discussion of air fresheners used by Alice to mask the smell of her dog in Section 6.4.1.3, the interpretations of the participant and ADF are very different: the participant is adding something into the air which from their perspective improves the indoor environment, however from the technical perspective of ADF the candle introduces additional pollution and therefore requires additional ventilation.

As discussed in relation to the mould issue above, the automatic boost function of the continuous MEV system would not be triggered by the pollution caused by burning candles. This meant that there was no route by which the pollution from the candles would be mitigated using the planned ventilation system.

As noted at the beginning of this section, although the ventilation strategy allows for extract ventilation to continually remove water vapour or pollutants from significant sources a continuous MEV with automatic controls precludes this in general (although some sources could be continually removed if they trigger the automatic controls). The example of mould brought up by the Alice and Darren gives an example where this technology could cause a problem. The example of Brandon's candles combines the technology problem with a lack of formal knowledge of pollution sources and this could be a cause of the lack of action by the participant to mitigate this source of pollution.

The presentation of the participants' practices related to ADF's idea of extract ventilation has so far referred to the intended technology of the continuous MEV only briefly. The following section discusses this technology in relation to extract ventilation.

6.4.2.5 What about the intended technology?

The sections above have shown that the participants had meanings associated with limiting the spread of (things perceived to be) pollutants around the dwelling, but there has been little discussion of the intended technology. Although the continuous MEV did not have a boost function as intended according to ADF, some of the participants had the impression that it did deal with some of the pollutants produced associated with specific activities:

DARREN There's not fans, there's these (*Darren points to the terminal on the kitchen ceiling*), which I presume are taking some of the smells away and stuff like that, there's another one in the bathroom which doesn't have a fan, although I haven't really checked...Maybe there'll be a noise when I switch that on. (*Darren switches the* *light on and pauses to listen.*) Yeah so there is that but it doesn't seem to do anything.

Darren associates the continuous MEV with removing some smells from the home, although this is stated tentatively. The expectation that the bathroom extract comes on with the light is drawn from his experience in previous homes, but the lack of noise means that Darren has no indication of the whether switching the light on causes the extract to come on.

Alice similarly is unsure if the MEV is working, Aaron on the other hand uses the clearing of condensation in the bathroom after a shower as an indicator:

ALICE Obviously marginally more stuffy in the bathroom because it doesn't have a window. It's got a silent fan, but obviously post shower or anything it's very, it takes a while for all of that steam etcetera to dissipate.
(*Later on*)

ALICE Clears within about 10 minutes. Yeah, it's very, there's condensation everywhere, it's covered, but it seems to go within about 10 minutes

AARON Yeah! Like our fan is like...

ALICE I don't know what it's doing, if it's doing anything.

AARON It's probably doing, ah, I don't know what it's doing but whatever it is it's pretty good. Tiny little fan, doesn't make any noise.

The quotes above illustrate that the participants assess the functioning of the MEV in different ways. There is some suggestion that the continuous MEV removes condensation and smells but this is stated tentatively and the participants lack a means of verification or reassurance of the functioning of the system.

6.4.2.6 Extract ventilation summary

The participants had meanings corresponding to the ADF purpose of extract ventilation: to remove water vapour or pollutants in particular locations and prevent their spread to the rest of the building. Sometimes this included things that should have been taken into account by the whole dwelling ventilation according to ADF, such as the provision of 'fresh' air.

The participants again showed that manipulating the air was related to broader considerations than just the smells or compounds in the air, including thermal comfort, noise and privacy. Although some of these are briefly mentioned in ADF, there is no detailed consideration of how this might affect the actual ventilation in practice in the dwelling, particularly as relates to extract ventilation rather than purge ventilation.

Additionally, this section has shown how the practice of manipulating the air can be understood as dispersed. The practice appeared in relation to integrative practices of showering, cooking, getting ready to sleep, as well as other dispersed practices such as thermal comfort at home.

The technologies the participants used in controlling the location and spread of water vapour or pollutants were dominated by doors, windows and the cooker hood. ADF intends for the boost rate of the continuous MEV to provide this function, but in these flats, there was no boost rate, so it was not possible for ADF's intention to be realised. Even if the system had worked in accordance with the plans provided by the developer, the participants would not have been able to control the continuous MEV, so if they had wanted to control the spread of pollutants themselves they would have had to use alternative technologies. Moreover, the boost rate of the continuous MEV would mostly influence airborne pollutants, whereas the participants' used the other technologies to control heat and noise flows, as well as for privacy.

Finally, by placing the MEV in the kitchens, bathrooms and utilities, the planned ventilation system builds in the assumption that high water vapour or pollution loads will be generated in these rooms. The planned system is not designed to handle regular high loads of water vapour or pollution in other parts of the building (for example, Brandon's almost continuous burning of candles while he is at home), or continuous high loads in other parts of the building (for example, mould in bedrooms).

6.4.3 Purge ventilation: ventilation for one-off extreme events

This section compares the ADF intention with the participants' practices in terms of pollution from one-off or extreme events, in ADF these are dealt with using purge ventilation. The first part of this section describes how ADF intends purge ventilation to be provided in these flats. Section 6.4.3.2 presents the extreme or one-off circumstances in which the participants manipulated the air and Section 6.4.3.3 presents the participants' related practical understandings.

6.4.3.1 ADF expectation of purge ventilation

According to ADF, purge ventilation should be provided throughout the dwelling to dissipate significant high concentrations of pollutants or water vapour from occasional sources. For continuous MEV systems, purge ventilation is usually provided by open windows, although for rooms without windows it can be provided by the high flow rate of the continuous MEV. According to ADF, if the MEV is used for purge ventilation the controls should not be automatic and it is accepted that purge ventilation using this method is likely to take longer than if windows were provided.

At CS2, windows were provided except in the bathroom. As already discussed, the planned MEV system was supposed to have humidity based automatic controls which would not have matched the ADF requirements. Regardless, the system as installed did not appear to deliver increased flow rates so effectively there was no purge ventilation provision in the bathrooms at CS2.

Appendix B of ADF gives details of the size of windows required for adequate purge ventilation. This states that if the opening angle is less than 15° then the window is not appropriate for purge ventilation. The flats had multiple windows that could be tipped (hinging from the bottom of the window up to a maximum opening of about 10 cm at the top) or tilted inwards (unrestricted hinge on the side of the window), see Figure 6.3. When the windows were tipped the opening angle was about 5°, so according to ADF this was not sufficient for purge ventilation. The windows at CS2 would need to be tilted to meet ADF's standard for purge ventilation, Brandon noted that his windows could not tilt open and therefore purge ventilation was not available in Flat B.

6.4.3.2 Dealing with extreme unwanted conditions

In some instances, the participants mirrored the ADF purpose of purge ventilation with a practical understanding that significant unwanted smells can be dissipated

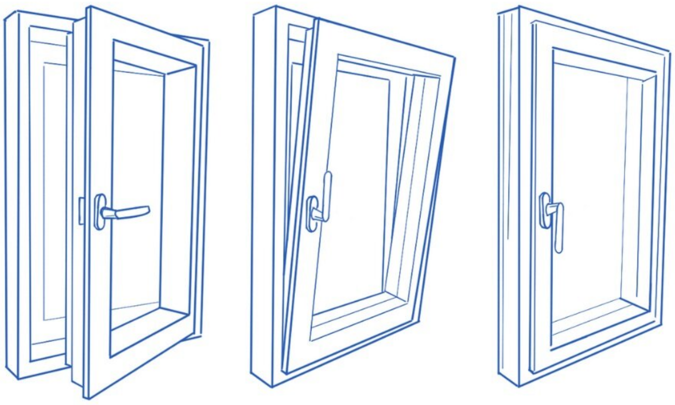


Figure 6.3: Schematic of the tip and tilt windows at CS2, from left to right the window positions are tilted, tipped and closed. Figure from Bauwerksolutions.com (2019).

through open windows. For example, the participants mention opening kitchen windows as a way to remove accidental smoke from burning food. Aaron gives a further example:

AARON If there's a few people in here we'd probably have to have them open, because otherwise it's a bit stuffy.

The presence of more people than usual caused an uncomfortable amount of stuffiness, with the practical understanding that opening windows can dissipate this.

However, as seen in the previous two sections, it was not only the excess of particular compounds in the air that the participants controlled through manipulating the air. For example, excess heat is dissipated through windows, for Darren this is almost the only time that windows are opened:

DARREN The only real times that I've felt like I have to open the windows were like when cooking on a really hot day, but that's not really to, that's kind of to let out the heat rather than anything else

In this case occasional excessive heat was dissipated through open windows, and it was the coolth of the outdoor environment which was desirable rather than the lack of particular compounds in the outdoor air.

Sometimes the opposite of purge ventilation was required:

> BRANDON Sometimes people smoke outside the window a little bit there so that's quite annoying [...] I'd kind of make a big point of slamming [the window] shut, so people could see it and hear it and maybe move away.

Brandon is frustrated by others smoking close to his home and the smell infiltrating into his home environment. Purge ventilation is the rapid dilution of the indoor air with outdoor air due to an occasional, significant source of indoor pollution, the situation here is very much the opposite in that the outdoor air contains a significant source of pollution and the participant wants to decrease the ingress of outdoor air as much as possible. This could be considered 'anti-purge' ventilation, the indoor environment contains a reservoir of unpolluted air rather than the other way around. Additionally, the windows are closed not only to limit the ingress of the smell of smoke but also in an attempt to communicate Brandon's frustration and make the smokers reconsider their actions.

This is related to the closure of windows due to excessive cold outdoors despite excess cooking smells discussed in the extract ventilation section (Section 6.4.2.2). In both cases the outdoor environment has become undesirable and it is important to the occupants that the outdoor environment is excluded. Although ADF raises the possibility that external conditions may limit the extent to which purge ventilation is feasible, this is only with reference to noisy external environments. The above discussion shows that a wider range of conditions affect whether opening windows is a feasible option.

It is also worth noting that Brandon's MEV system was switched off. Had it been switched on, then the cigarette smoke would have continued to be drawn into the flat by the continuous MEV despite closing the windows (albeit to a lesser extent).

6.4.3.3 Tipped or tilted?

It was noted at the beginning of this section that tipping the windows open at CS2 was not sufficient for purge ventilation according to ADF. However, it was very rare for any of the participants to tilt their windows open, Darren explained why he only tipped the windows open during very hot days:

DARREN I would just tip it and then that would be more than enough, so.

Darren has the practical understanding that tipping windows open is enough for dissipating the amount of heat he feels is required.

Brandon was not able to tilt his windows open, although he explained that he would not have done this even if it were possible:

BRANDON Because I'm on the ground floor people could have just walked in couldn't they.

With the windows tipped, Brandon feels the flat to be very secure but tilting the windows would have represented an unacceptable security risk. Similarly, although Cal could tilt his windows open, he very rarely did this:

CAL I would like maybe to keep the widow much more open, but because it's ground floor sometimes feel like, can I leave it open?

Cal was comparing his current flat with a previous home where his bedroom had a sliding balcony door. In his previous flat he had enjoyed opening the door and feeling connected to the outdoor world. Although Cal would have preferred to have his windows more open his concerns about security prevented this. Bridget was initially unsure about opening windows:

BRIDGET I ask Brandon on September if I can open the window on the day and he say 'yes, yes, I do all the time, don't worry is ok.' So I open the window and I just close when it's cold outside.

Bridget has a practical understanding that opening windows was required but sought rules from her landlord, Brandon, to confirm which actions she is allowed to take for security in her rented flat. While Brandon, Bridget and Cal all frequently tipped the windows open, including while the dwellings were unoccupied, Darren was concerned about safety with any amount of window opening:

DARREN I'm on the ground floor so anybody can just walk past here so [...] I don't want to open windows in case somebody can walk past and just like reach in or something like that [...] I mean that's why the blinds are closed all the time, because I'm very lazy about leaving my laptop out and stuff.

All the participants mentioned security in discussing their use (or not) of windows in their homes, although the extent to which this hindered their tipping or tilting of the windows varied. This shows how the same technology (windows which can be tipped or tilted) in very similar locations (ground floor or first floor flats in the same building) have been interpreted in different ways in terms of their affordance of security, and this has considerable consequences for the ways the flats are ventilated.

Aside from security concerns, tipping the windows open had other practical advantages compared to tilting the windows:

BRIDGET In [my home city] I don't have the same windows, I just have, my windows can just open in like this [tilt] not like this [tip] so on the day when I'm home if we have some wind, yes? Wind, windy it's a little bit boring because the windows open and close alone and make noise and so this is very practic[al].

For Bridget the ability to tip the windows meant that the windows could be open regardless of the wind outdoors, which was an advantage compared to tilting the windows in her family home. Weather was noted by other participants, for example that tipping the windows meant that there was little rain ingress.

There were also non-weather related advantages to tipping rather than tilting the windows:

AARON In the summer we open them, we open them fully in the summer and like usually, usually the bedroom. In fact not so much the bedroom one because like, you get those shitty little fly things don't you, so we just [tip] that one most of the year, but this one, or one of these two [in the living room] we'll always open fully.

JESSICA Mmm ok, so when you open them fully, because I just notice that the desk is there as well, would you have to move stuff around to be able to open them?

ALICE They are massively inconvenient windows. And also, when you open it fully that is an enormous space. I am quite conscious of the dog like climbing up and potentially jumping out of the window.

Both keeping unwanted things out of the flat (people, flies, weather) and wanted things in the flat (dog) were easier to achieve with the windows tipped rather than tilted. Moreover, because the windows tilted inwards this sometimes required an inconvenient rearrangement of furniture, this problem was also encountered by Cal.

The ability of the windows to tip and tilt allowed the participants to modify the amount of ventilation through open windows, but concerns such as security, safety, inconvenience and weather ingress often played a significant role in the extent of the participants' window opening. As a result, it was unusual that the windows were tilted open and the participants indicated that this was almost always associated with thermal comfort. Although the windows are capable of delivering the purge ventilation required by ADF, in practice the participants almost never use the windows in this way because of the practical difficulties associated with this.

6.4.3.4 Purge ventilation discussion

Similar to the previous two kinds of ventilation, the purpose of purge ventilation according to ADF could be translated into a meaning that the participants have around manipulating the air in their homes. However, the practical understandings of the participants are different to the actions ADF assumes the occupants will carry out. Considerations around safety, ingress of unwanted things and spatial arrangements of furniture in the dwellings reduced the extent to which the participants were willing to use the windows in the manner intended by ADF. Additionally, as seen in the previous sections, the participants dealt with a far greater variety of conditions than ADF; the participants controlled one-off and extreme heat flows, unwanted smells from outdoors as well as dissipating excess internally generated pollutants.

This and the previous two sections have compared the participants' practices with the ventilation strategy set out in ADF, which splits the ventilation into three types. These sections have compared ADF's purposes, technologies and implicit occupant actions with the participants' practices of manipulating the air. However, some aspects of the participants' practices were not captured within the ADF structure, the following section discusses those aspects.

6.4.4 What does not fit into the ADF ventilation strategy?

There were aspects of the participants' practices which were important to how the participants manipulated the air in their homes but did not fit into the ADF structure. For example, the participants appreciated the feeling of being connected to the outdoors through letting outdoor air come into the home:

ALICE rather than having like the smog of London coming in the window, it's quite, it's like nature, it's like having a bit of nature
(*Later in the interview*)

ALICE I like the outside being in. And I feel, perhaps irrationally even, claustrophobic if windows are closed for too long or anything like that

This feeling of claustrophobia might seem to be extreme case, but recall that Darren used the word 'suffocating' to describe his sister's flat when it did not have outdoor air following cooking. Gram-Hanssen (2010a) also reported similar sentiments from a participant who spent a significant part of the year living on a sail boat. Other participants expressed this less strongly but were also keen to let outdoor air inside:

CAL I just like the idea of having fresh air and it just, and having that contact with the outdoor in that sense

Sometimes specific attributes of the outdoor air were particularly desirable, Darren explains why he likes the air at his parents' house so much:

DARREN They've got such a nice garden with loads of flowers all the time, so the smell of that always comes in.

He also references enjoyment of sounds from outside at a previous home:

DARREN It's been the sounds that I'd kind of miss [here], in previous places it's been a park, it's been middle of suburban nowhere and farmland with loads of birds, so that's one thing that I have missed

In the ADF view, outdoors is essentially a reservoir of air free from pollutants. These parts of the interviews revealed that the outdoors has a much more pleasant role to play in the participants' manipulation of the indoor air.

Hauge (2013) discusses the role of ventilation in feeling connected with the outdoors in detail. She frames air an intermediary between home and nature, in which allowing outdoor air into the home blurs the boundary between indoors and outdoors. Hauge's study took place in Denmark, but the above quotes from the participants suggest these participants share meanings associated with bringing outdoor air into the home in order to feel connected to nature and the outside world. The participants all have the practical understanding that windows are opened in order to achieve this.

6.4.5 Overall how similar are the ADF intentions to the participant practices?

Having presented a detailed comparison of ADF's different types of ventilation with the participants' practices of manipulating the air it is now possible to discuss the recurring similarities and differences between two.

6.4.5.1 ADF's purposes for ventilation are found in the participant's practices

In each of the sections above it was shown that the purpose ADF attributed to the different kinds of ventilation corresponded to an extent with meanings that the participants had. For example, the whole dwelling ventilation Section (6.4.1) showed that the participants had meanings associated with the freshness of indoor air and with dissipating water vapour or pollutants within the home. This similarity was also observed for extract and purge ventilation. However, the participants deviated from ADF in terms of how they dealt with, and what they considered to be, 'pollution'. This is discussed in the following sections.

6.4.5.2 Participants' practices are contextual

It has been shown above that the participants carried a dispersed practice of manipulating the air in their homes. This practice was woven into the fabric of their domestic lives, appearing in many situations and in conjunction with many other practices taking place in the home. For example, manipulating the air came up in relation to practices like showering, cooking, hosting, getting ready to sleep and maintaining thermal comfort.

Understanding how the participants manipulated the air in relation to other practices requires considering aspects of the indoor environment other than airborne pollutants and odours alone. Aspects such as temperature, sounds, security or the existence of pollution outside (e.g. smokers close to the building) are taken into account by the participants when they choose how to manipulate the air in their homes. For example, the participants have a meaning related to limiting the length of time over which cooking smells are detected (this corresponds to the ADF aim of extract ventilation to remove water vapour or pollution from significant localised sources) but the participants will reduce their window opening and tolerate stronger cooking smells in the winter to achieve better thermal comfort. ADF references some of these aspects, but not in any way that significantly affects the recommended ventilation systems. For example, ADF notes that windows may be opened in the summer to provide thermal comfort, but does not consider an alternative for purge ventilation in the winter when opening windows could cause thermal discomfort. In this sense, although ADF acknowledges that there could be factors other than indoor pollution which affect ventilation, it has no built-in contingency for these situations. In contrast, the participants pay attention to these various factors and modify the way they manipulate the air accordingly.

6.4.5.3 The installed ventilation system does not match the ADF strategy

There were ways that the ventilation system as installed prevented the ventilation strategy from being carried out. As discussed in Section 6.4.2 the ADF continuous MEV system presupposes the locations that most water vapour and pollution will be produced. This means that the occupants could not use the technologies intended to provide extract ventilation to deal with significant sources of pollution in other locations, even if the system had worked as planned. The cases of mould and candles were discussed in particular: such sources are not easily dealt with by the planned ventilation system.

Moreover, the ventilation systems at CS2 did not provide boost ventilation. This means that water vapour or pollutants which ADF intends to be removed by extract ventilation are instead dispersed through the dwelling. Any response to these high loads of pollution and moisture must come about as a result of occupant actions rather than via the planned automatic system. The difference between the participants' use of ventilation technologies and ADF's intentions is discussed in the following section.

6.4.5.4 Participants' use of the ventilation technologies is different to ADF intentions

The ADF system couples the purpose of the ventilation with the technology and actions intended to achieve this, but the participants' approach rarely mirrored this. In particular, the continuous MEV and trickle vents were core to the ADF system but featured minimally in the participants' practices. In contrast the windows, doors, cooker hood and air fresheners had limited or non-existent roles in the ADF system but were key components of the participants' practices. The role of air fresheners will be discussed in the following section with further reference to indoor pollutants, this section discusses how the ventilation technologies were used between the participants and ADF intentions.

The windows were an important technology for the participants, whereas in ADF the windows were only involved in purge ventilation. According to ADF the windows were only sufficient for purge ventilation when they were tilted open as the angle of opening when the windows were tipped was too small. Although tilted windows would sometimes have been preferred for greater connection to the outdoors, other factors such as safety, security, weather and inconvenience meant that the participants tipped the windows most of the time. Window use was associated with daily routines and other activities in the home. Moreover, many of the practical understandings of manipulating the air involved using the windows in cases where ADF expected the continuous MEV system to be sufficient, for example for providing fresh air, or for dissipating smells generated while cooking.

Similarly, doors were woven into many aspects of domestic life, from sleeping, cooking, showering, laundering and maintaining social relations. Doors were also strongly involved in limiting the spread of smells, transmission of noise or heat flow within the building. For ADF, limiting the spread of pollutants is limited to airborne pollutants and water vapour and is intended to be carried out by the boost rate of the continuous MEV. Doors play little role in the ADF system, with the only reference regarding the requirement for an undercut to facilitate the flow of air around the building. These undercuts limit the extent to which the doors are effective at limiting the spread of pollutants (as interpreted by the occupants), although the participants did not raise this as a concern.

The continuous MEV was a core component of the ADF system, but there were no associated practical understandings as the system provided a continuous flow rate. Kuijer (2019) discusses the difference between polimorphic and mimeomorphic actions: mimeomorphic actions are always performed in the same way, whereas polimorphic actions are carried out differently depending on the social context. Kuijer discusses this with reference to the delegation of washing clothes to washing machines. Washing machines carry out a mimeomorphic action in that they treat all clothes in the drum in the same way, whereas a person washing their clothes by hand would (or could) pay attention to the shape, textures, location of stains or significance of items (for example a well-loved hand-knitted jumper versus a tea towel) and thus carry out a polimorphic action when washing clothes. In the case of the ventilation system investigated here, the continuous MEV is performing a mimeomorphic action: constantly extracting air at the same rate regardless of the conditions in the flat. Manipulating the air has been shown to be polimorphic, the participants' requirements for replacement of indoor air with outdoor air depends on many factors, as shown above. Although some of the work of ventilation has been delegated to the continuous MEV the participants still need to pay attention to the air and manipulate it when it does not have the appropriate qualities.

It is not obvious how an automated technology such as the continuous MEV can be interpreted within the SPT framework as it is not a technology with which people interact, Gram-Hanssen (2019) discusses this. Gram-Hanssen gives an example of automatic whole house heating which people do not interact with and speculates that indoor practices of staying thermally comfortable might become more similar to those practices outdoors. If the practitioner has no control of the heating (as when they are outdoors) then they must find ways to get an appropriate level of thermal comfort without affecting the temperature of the environment themselves. This is similar to the continuous MEV system; the participants have no control of the system (except to switch it on and off). The continuous MEV affects the air in some ways that the participants do not control and the participants must react to the air that they find in their home as a result. The resulting air in the home might or might not be interpreted as acceptable. If the air is not acceptable then the practitioners have to take matters into their own hands to manipulate the air in the ways they deem appropriate in order to obtain acceptable indoor air. These practical understandings of manipulating the air are necessarily through interactions with other technologies, most commonly windows, doors, cooker hoods and air fresheners, as the participants are unable to influence the working of the continuous MEV.

As well as the lack of interactions with the continuous MEV, the participants also had no formal knowledge or rules relating to this technology. The Domestic Ventilation Compliance Guide (DVCG) states that end users should be handed over information including an 'operation and maintenance manual [which] should contain specific instructions for the end user on how and when to use the ventilation system' HMG (2010e, p. 53), but these participants could not recall ever receiving advice or instructions about the MEV system. Several of the differences between the ADF intention and the participants' practices show that rules and formal knowledge have not contributed to shaping the participants' practices. For example, the participants occasionally used the trickle vents whereas ADF intends the vents to be continuously open, the participants had never received an instruction or advice that the vents were supposed to be continuously open so their practices have not been informed by this rule.

The participants' lack of formal knowledge or rules in this study contrasts with Behar's (2016) participants who were housing association tenants and had received advice in the form of leaflets and home visits after moving in. Behar's participants could often recall being instructed on the use of their ventilation systems. Whereas the participants of Behar's study were, at least sometimes, aware of rules regarding their ventilation systems, it is striking that none of the participants in the current study were. Possible sources of advice could have been bodies like NGOs; Gram-Hanssen (2010a) discusses a participant with asthmatic children whose airing practices had been shaped by the advice of an asthma charity. This was in Denmark, but there are public bodies in the UK which give ventilation advice. For example, some of PHE's key public health messages regarding heatwaves include advice to open windows at night (PHE, 2019). Energy efficient retrofits of existing dwellings in the UK are required to provide the occupants with appropriate advice, at least at the commencement of the project and at the time of, or shortly after, completion (BSI, 2019). This includes advice regarding the use and maintenance of new technologies installed as part of the retrofit. If delivered well, such requirements could embed appropriate rules and practical understandings for new technologies. This may be appropriate in both new build and retrofit contexts.

6.4.5.5 Importance of smells and lack of formal knowledge or rules regarding indoor air pollutants

The participants' practices were strongly influenced by their perception of the air in terms of its scent and stuffiness. The meanings the participants associated with different smells begins to show how important the olfactory landscape is key to understanding why particular actions were associated with particular smells. From the smell of a dog, the temporal appropriateness of cooking smells, the taboo of smells associated with the toilet or the boosting of the scent of freshly laundered clothes, different smells influenced the participant's practices in different ways. Classen et al. (1994) discuss the cultural significance of smells, highlighting how smells can be highly evocative, related to various cultural and personal symbols from gender and social standing or reminiscent of particular people and events. The diversity of different smells and their various social significances is belied by ADF's uniform approach to 'odours' and the assumption that these will be removed by ventilation.

Another key difference between the participants and ADF concerns what is considered, or known to be, an airborne pollutant. This was particularly apparent where the participants used air fresheners or scented candles to improve their perception of the air. Concerns about health implications of the air in their homes were associated with pollutants which the participants had a direct perception of; those that were 'coughy', smelt 'a bit off' or were associated with more colds. When the participants had such direct perceptions, they were invested in reducing their exposure to those pollutants which were perceived to be causing the problem. However, none of the participants had formal knowledge or rules related to mitigating indoor pollution from sources which have no significant smell or a pleasant smell. These kinds of sources could include cleaning products, personal hygiene products, dust from vacuum cleaning and VOCs released by furnishing and fittings (Shrubsole et al., 2019a). For ADF, pollution from these kinds of sources are intended to be removed by the ventilation systems.

By contrast, the participants often did have formal knowledge of outdoor air pollution:

BRANDON I know that primary schools are all up in arms, aren't they, about air quality outside their schools aren't they and stuff.

Here Brandon was drawing on information from news articles, something that Bridget also mentioned in referring to her home country and city and Cal had an app which reported the outdoor air quality. Formal knowledge of outdoor pollution had been gained from news sources and apps, but the participants did not have similar sources of information relating to indoor pollutants. For example, Clean Air Day's messaging about indoor air pollution advises window opening when cooking and cleaning (Cleanairday.org.uk, 2020), but none of this kind of advice or formal information from such organisations has reached the participants of this study. Given that the participants have no direct perception and have no formal knowledge or rules relating to the potential indoor pollution caused by things like cleaning products, scented products, candles or new carpets it is not surprising that their practices of manipulating the air do not reflect the intention in ADF regarding dilutions of these kinds of pollutants.

This part of the chapter has discussed the day-to-day ventilation in the participants' homes with reference to ADF and the participants' practices, the maintenance of the ventilation systems is addressed in the following section.

6.5 Maintenance of the ventilation system: participants, ADF and manufacturers

As mentioned above, the DVCG (Domestic Ventilation Compliance Guide) states that end users should be given an 'operation and maintenance manual [which] should contain specific instructions for the end user on how and when to use the ventilation system' HMG (2010e, p. 53). This section presents how ADF and the manufacturers refer to maintenance of the ventilation system, and then goes on to discuss the participants' maintenance of the ventilation system.

6.5.1 ADF and maintenance

ADF only briefly references maintenance. ADF states that ventilation systems should be 'installed to facilitate maintenance where necessary' (HMG, 2013b, p. 13) and that there should be reasonable access for 'the purpose of changing filters, replacing defective components and cleaning ductwork' (HMG, 2013b, p. 19). At CS2 there were no filters in the MEV. The recirculating cooker hood had filters but this was not part of the required ventilation strategy. Access to the continuous ventilation system and ducts was via a ceiling access panel, see Figure 6.4.

Figure 6.4: Ceiling access panel in the utility cupboard at CS2 for the continuous MEV system and ducts.

6.5.2 Manufacturers and maintenance

The continuous MEV product information instructed that the system be installed with adequate access for maintenance (similar to ADF), however the fan itself was not expected to require maintenance (Vent-Axia, 2020).

Installation instructions for the trickle vents installed at CS2 were not available, but the product specifications made no reference to maintenance requirements (Greenwood, 2020). However, installation instructions for a different model manufactured by the same company simply had a section titled maintenance, which recommended that ‘any dust be simply removed from the internal mechanism without dismantling’ (Greenwood, 2003, p. 2). No further detail regarding frequency or instructions were given.

The manufacturers of the continuous MEV and trickle vents give indications that maintenance of the equipment may be necessary, but very little detail is provided (similar to ADF). The following section explores whether the participants maintained their ventilation systems.

6.5.3 Did the participants maintain the ventilation system?

This section is split into parts discussing the cooker hood, continuous MEV system and trickle vents.

6.5.3.1 Cooker hood

Although the cooker hoods were not a required component in the ventilation system, they were a technology that the participants frequently used (see Section 6.4.2.2).

At the time of the interview, Alice and Aaron's cooker hood had stopped working:

JESSICA So [the cooker hood is] broken at the moment, do you know what's wrong with it?

AARON I think the filter needs changing and it needs cleaning out. But I mean, I don't know. Yeah, but that would be my guess.

Alice had been at home when a maintenance person visited and found that there was a different problem (it was unclear what this was). Although it was known that the filters could be changed Aaron and Alice have never done this, they were seeking help with maintenance of the cooker hood because it had stopped switching on rather than as a regular action of on-going maintenance. Brandon is aware that cooker hoods can stop working because his sister's had broken, but he indicated that only in the event of the cooker hood no longer turning on would he carry out or seek maintenance.

In contrast, Cal has recently noticed a maintenance record sheet stuck onto a unit in the cupboard adjacent to the cooker hood, see Figure 6.5. Cal has interpreted this as being associated with the functioning of the cooker hood, although it specifically relates to the fire suppression system within the cooker hood.

CAL I think [the service is] yearly but it's just kind of come and check that everything's alright, but I need to actually get in touch with them.

Although Cal is keen to get the cooker hood serviced, he does not know how to arrange it. Here, Cal has identified a rule associated with the cooker hood, but does not have practical understandings related to organising to have the cooker hood serviced.

Since the flats were all converted at the same time by the same developer it is very likely that the other participants had the same maintenance record sheet as Cal in the cupboards next to their cooker hoods, however none of the other participants mentioned this in

Figure 6.5: Maintenance record sheet and system status indicators on the cooker hood fire suppression system in Flat C.

discussion of the cooker hood and it's maintenance (unfortunately Cal was interviewed last so the other participants were not prompted about the maintenance record sheet or indicating lights).

6.5.3.2 Maintenance of the continuous mechanical extract ventilation

Only Cal gave any indication of an intention to carry out maintenance on the continuous MEV system. The fan flow rates were measured immediately following the interview in Flat C, this involved using a step ladder so that the flow hood could comfortably be held in place during the measurement. Upon seeing the step ladder, Cal asked if he could borrow them after the measurement to clean the dust that had visibly built up around the extract terminal in the bathroom. He stated that he had wanted to clean this area for some time but having no step ladder available he had been unable to do this. In this case, the maintenance of the system was linked to a meaning associated with cleanliness of the home, but a lack of appropriate technology (step-ladders) had prevented this from taking place earlier. As discussed in the previous chapter, this cleaning doubled the flow rate through the bathroom extract.

6.5.3.3 Trickle vents

The participants indicated that they only ever opened and closed trickle vents and had never carried out any maintenance or cleaning on them.

6.5.4 Maintenance discussion

The participants were usually unaware of any maintenance requirements for their ventilation equipment, or had limited relevant practical understandings. Introduction of new maintenance requirements is discussed by Ariztia et al. (2019) who studied the introduction of kerosene domestic heating systems in homes which previously used wood-fuelled heating in Chile. Maintenance of the old wood-fuelled stoves was carried out as part of the daily cleaning practice, whereas maintenance of the kerosene system required a very different kind of schedule, one that involved technical expertise, reading manuals and receiving instructions from installers. It was thus shown that the new technologies required new repertoires of practice for maintenance of the system. This situation is somewhat similar to the ventilation system at CS2 in that technology new to the occupants has been introduced in these homes which may require new forms of maintenance practice, potentially involving actors from outside the household. However, the extent to which the participants at CS2 were aware of maintenance requirements was very limited.

At CS2, no technical expertise, manuals, instructions from installers or any other form of rules regarding the maintenance of the systems were recalled by any of the participants (with the sole exception of Cal's knowledge of a maintenance record sheet for the fire-suppression unit on the cooker hood). The DVCG requirement that adequate information for maintenance is communicated to the end-users has not resulted in these participants being aware of any on-going maintenance requirements.

When cooker hoods had stopped switching on the participants knew that this needed fixing. As discussed in Section 6.4.2.2 the cooker hoods were used deliberately and there were several indications that the technology was working. In contrast, it is not clear whether and how participants would have noticed if the continuous MEV system had stopped working since there were no practical understandings and few ways that the participants could interpret its functioning. For example, Brandon had no knowledge of the system or that it was switched off. This means that it seems unlikely that the participants would have the relevant practical understandings to find out whether the MEV needed maintenance.

Finally, even where Cal wanted to clean the extract terminal in his bathroom, he lacked appropriate technology to allow him to reach the terminal. Even though the ventilation system is required to be installed to facilitate maintenance this was not realised in practice.

Maintenance of the ventilation system is not a practice that the participants of this study carried out. The participants showed some meanings associated with maintenance when technology was easily interpreted as not working, and some meaning related to cleanliness. However, there were very few practical understandings, either related to knowing when maintenance might be required, or how to carry this out, and there were no formal knowledge or rules relating to maintenance. Moreover, Gilbert (2014) notes that there are no large scale maintenance schemes for residential ventilation systems in the UK, this suggests that maintaining ventilation systems is not a commonplace activity in homes.

This is a clear area for further research, since Cal's cleaning of the bathroom terminal resulted in a doubling of the flow rate, and previous research has identified issues with trickle vents including improper installation and reduced vent areas due to painting over (Fox, 2008; Sinnott, 2016). This is discussed further in the following chapter which brings together the social and technical findings.

6.6 Summary

This chapter presented the results of the comparison between ADF's assumptions about how ventilation systems will be used and the participants' practices. It was shown that ADF implicitly assumes that occupants take certain actions in their homes in order that the ventilation strategy and systems function as described. This intended functioning was compared with the CS2 participants' practices of manipulating the air using the SPT framework given in Gram-Hanssen (2010a).

ADF's purposes for ventilation were broadly mirrored in some of the meanings the participants attached to manipulating the air in their homes. For example, the participants' wanted 'fresh' air in the home, and in some instances were keen to limit the spread of (broadly defined) pollutants around the dwelling, aligning with ADF's stated purposes for whole dwelling and extract ventilation respectively. But there were several important reasons that the participants' practices differed from ADF's intentions.

ADF considers ventilation only in terms of the removal of pollutants and water vapour whereas the participants' practices of manipulating the air were much more diverse. The practices were informed by the social significance of different smells in the home, feelings of freshness and stuffiness and connection and communication with the world outside, none of which are apparent in the ADF approach. These aspects are relevant for understanding why it is that occupants do not use ventilation equipment in the ways set out in technical guidance; it is possible that ventilation systems and guidance which are designed with such considerations in mind may perform better when installed in homes.

The participants' practices were shown to be much more nuanced than the description of ventilation in homes given in ADF. Manipulating the air involved noise, temperature, outdoor pollution and enjoyment of the outdoor environment. Moreover, the social significance of different smells meant that they were handled differently, in contrast to ADF's blanket treatment of 'odours'. Also, the participants modified the ways they manipulated the air with reference to this wide variety of conditions, whereas there is no contingency in the ADF strategy for conditions other than indoor air pollution to affect the way ventilation happens.

The participants' manipulated the air in relation to many different practices in the home (both integrative and dispersed), including cooking, showering, maintaining thermal comfort, getting ready to sleep. Because the participants were paying attention to a wide variety of conditions in the home arising in the context of different practices, the circumstances in which they took actions to affect the air were much broader than those outlined in ADF.

Moreover, the use of the ventilation equipment often did not match the intention in ADF. Some of this was because the intended functionality of the system was not realised in the homes as-built, in particular the MEV had no boost flow rate. This meant that it was not possible for all of ADF's intentions to be realised in these homes. Beyond this issue the participants' use of the ventilation equipment was different to that intended in ADF. The participants' practical understandings largely involved using windows, doors, air fresheners and cooker hoods, whereas the continuous MEV and trickle vents were dominant technologies in ADF. ADF intends very few interactions with the trickle vents and MEV, only that they are open and on. However, the participants had very little formal knowledge or rules regarding these technologies, the trickle vents were almost always closed and the MEV was off in one of the flats with the occupants unaware of this.

Furthermore, the participants had limited formal knowledge or rules relating to indoor air pollutants. The participants were keen to control the strength and timing of particular smells or ‘stuffiness’, and in some cases they had direct personal experience of adverse health effects caused by pollutants (particular air fresheners, mould). However, they had no formal knowledge of sources of pleasantly scented or unscented harmful pollutants in their homes, for example those associated with cleaning products, personal hygiene products or candles. Their practices did not involve limiting their exposure to such pollutants in the way that ADF might expect.

Finally, the maintenance of the systems was discussed with reference to the intentions of ADF, the product manufacturers and the participants practices. Cooker hoods had been repaired when they stopped switching on, but this is a technology with which the participants regularly interacted. It is not clear how the participants would become aware if the continuous MEV were to stop working since they already had very few indicators of its functioning. In the single instance that maintenance of the MEV arose this was related to meanings of cleanliness. Although the DVCG states that end users should be provided with a manual including maintenance requirements, these participants were not aware of ever having received advice regarding maintenance of the systems. Moreover, the ventilation equipment literature produced by the manufacturers had no clear instructions regarding maintenance of the equipment. The participants had no clear practice related to maintenance of their ventilation systems. There are a few examples of social research relating to maintenance, for example Ariztia et al. (2019) studied maintenance practices following the upgrade of a heating system and Salvia et al. (2015) studied factors influencing maintenance and replacement of vacuum cleaners. Maintenance of ventilation systems is an important area for further research as there currently seems to be very little literature available. This is particularly the case regarding research of a socio-technical nature, which is likely to be important as this topic cuts across issues relating to the performance of a technical system and the actions of occupants in their home environment.

The following chapter will draw together the insights from this work with the physical results from the previous two chapters and discuss these findings.

Chapter 7

Conclusions

Indoor air quality (IAQ) can have serious implications for people's health (NICE, 2020b), which is particularly important given that many people spend the majority of their time indoors (Klepeis et al., 2001; Kornartit et al., 2010). Ventilation is an important factor in controlling IAQ as it dilutes the concentration of internally generated pollutants (RCP, 2016). However, if a building is thermally conditioned then increased ventilation rates increase their energy consumption (CIBSE, 2015). This is significant because countries around the world have agreed to reduce their CO_2 emissions through the Paris Agreement (UNFCCC, 2015) and buildings are a significant contributor to such emissions (CCC, 2020).

In the UK, steps have been taken to reduce excessive ventilation through infiltration in order to reduce carbon emissions associated with domestic space heating. The CCC report to the UK Parliament in 2020 highlighted the importance of testing actual, as opposed to modelled, performance of dwellings in the context of the requirement to reduce carbon emissions (CCC, 2020). In the case of ventilation in occupied homes, ZCH (2016) found that there could be a performance gap between the actual and expected performance of ventilation in homes. There has been considerable research into the ventilation of homes, but few empirical studies have been undertaken in occupied homes. Moreover, ventilation rates vary depending on occupant actions and weather conditions, but research has typically not addressed the variable nature of ventilation rates. Without accounting for such variability it is unclear to what extent ventilation systems are performing as intended. This thesis has investigated ventilation in occupied homes, it has generated detailed insights by exploring the variability of ventilation that occupants may experience and exploring the interconnectedness of the technical and social contexts in the home.

This chapter discusses the main conclusions and implications from the previous three chapters; the first reported on the development of an extension to the CO_2 decay technique to facilitate measurements in occupied homes, the second reported on the application of this method in a series of case study dwellings to investigate the adequacy and variability of ventilation rates, the final results chapter presented a comparison between the assumed uses of ventilation technologies implied in ADF and participants' practices. Then Section 7.4 presents a global discussion of the insights and implications available by combining each of the strands of research. This highlights some of the complexities associated with providing adequate ventilation in occupied homes. Finally, Section 7.5 summarises the main conclusions.

7.1 Ventilation measurement method in this research

As outlined above, it is common for ventilation research to either average ventilation rates over days or weeks, or to take small numbers of 'snapshot' measurements which average over minutes or hours. Neither of these approaches support a detailed understanding of the ventilation rates that occupants are likely to experience since ventilation is highly variable due to changes in driving forces (wind and temperature difference) and occupant actions (window, door and mechanical ventilation use). This research aimed to develop a method for ventilation measurement to facilitate research investigating the variability of ventilation rates in occupied dwellings, this was presented in Chapter 4. This method was based on the tracer gas concentration decay technique with metabolically generated CO_2.

The CO_2 concentration decay method requires that there are no sources present, so the measured space must be unoccupied during measurement. However, previous applications of this method have relied on assumed or reported occupant schedules or visual identification of unoccupied times (Roulet and Foradini, 2002; Guo and Lewis, 2007; Bekö et al., 2010). These methods were not appropriate for this research, which sought to investigate the variability of ventilation over extended measurement campaigns in occupied homes. An occupancy status algorithm (OSA) was developed which used CO_2 concentration, door and window opening data to determine when the space was occupied. This was tested using state-logging door sensors, no window sensors, in an occupied flat and the algorithm was found to agree with the occupants in 87% of cases. The inclusion of window sensors and event monitoring was identified as likely to improve the accuracy of the classifications by the OSA. These improvements were subsequently deployed in four occupied flats at CS2.

Whilst it was not possible to test the efficacy of this revision to the method, it is expected to have greater accuracy since window monitoring will detect cases where use of windows causes increased ventilation rates meaning that CO_2 does not rise, and event monitoring will detect cases where doors and windows are opened and closed in quick succession.

The results of the OSA were used to separate the data into periods when the dwellings were occupied and unoccupied, the analysis algorithm then identified and analysed periods of ΔCO_2 decay for single-zone ventilation rate analysis using the data from periods when the dwellings were unoccupied. This combination of the analysis algorithm and the OSA facilitated many ventilation rate measurements in occupied homes. The analysis algorithm identified periods of time where the CO_2 concentration was spatially homogeneous to comply with the assumptions of the technique. Measurements were averaged over a maximum of 90-minutes, this allowed exploration of the variability in ventilation due to different weather conditions and due to occupant use of doors and windows. Additionally, limits were placed on the variation of external CO_2 concentration during ventilation rate measurement periods, which resulted in between 4% and 46% of the decays being rejected for the cases studied. This highlights the importance of coincident external CO_2 measurement, particularly where measurements take place over an extended period.

The uncertainties associated with the measured ventilation rates were presented in detail in Section 4.3. The uncertainties associated with the measurement of ΔCO_2 and with the spatial inhomogeneity of the measured spaces were quantified. The effect of spatial inhomogeneity dominated the quantifiable uncertainty and the mean combined uncertainty was between 9% and 13% of the measured ventilation rate for all cases studied. Several sources of unquantifiable uncertainty were also identified, these included definitional uncertainty, the effect of ventilation dead-zones, uncertainties associated with the analysis algorithm developed in this research and the effect of flows between adjacent spaces. The serendipitous monitoring of two adjacent flats provided useful insights regarding the extent of leakage between two flats in this research.

There are several important limitations of the method developed to measure ventilation rates. Firstly, the number of ventilation rates measured depends on the way the participants use their home. Flat A was infrequently unoccupied because one of the participants worked from home, they also very often had windows open (close to 98% of unoccupied time and 80% of occupied time during the measurement period) meaning that CO_2 concentrations were generally low and appropriate periods for ventilation rate analysis were uncommon. As a result, far fewer ventilation measurements were recorded in Flat A compared to the other dwellings at CS2. Nonetheless, the low CO_2 concentrations and frequently open windows indicate that the ventilation rates in this flat were usually adequate for dilution of indoor sources of pollution, but that heat loss was likely high during the winter. Secondly, only configurations in which the occupants leave the dwelling unoccupied can be measured, unless the participants are willing to leave the dwelling in configurations stipulated by the researcher (this was not the case for this research). Thirdly, the CO_2 decay method is solely used for single-zone analysis of ventilation rate, the ventilation rates during periods that the CO_2 was not homogeneously distributed were not analysed. The spaces studied were reasonably small, but this requirement could have significant impact in large dwellings with few occupants. Finally, although the researcher time burden is reduced by the OSA and analysis algorithms, a significant amount of data collection, equipment and campaign management is required, so the method is resource intensive.

Despite these limitations, the method has been successfully implemented to give a detailed picture of the ventilation rates in the studied dwellings. The metadata (windows, doors, weather, fan flow rates etc.) combined with the OSA, and time-resolution of the ventilation rate measurements combine to give highly detailed insights into the ventilation experienced in case-study homes. This more nuanced understanding of ventilation in occupied homes is a useful tool in the context of understanding whether adequate ventilation is experienced in homes as-occupied, and in relating occupant practices to physical conditions, both of which are useful in considering guidance for ventilation systems.

7.2 Variability of ventilation in occupied homes

The exploration of the variability of ventilation rates at UTH and CS2, facilitated by the analysis methods and meta-data gathered, produced several insights. UTH was built in the 1930's and is an unoccupied semi-detached test house in Loughborough (England). Four flats at CS2 were investigated, CS2 is in London (England) and was built as an office in the 1980's and was converted into a housing development of over 100 flats in 2015. The influence of wind and temperature difference as driving forces on ventilation rates were explored at UTH and CS2. At UTH, simple models could predict the ventilation rates in the single measurement room with its door closed with an RMSE less than 0.1 ach for the best performing models, although different models performed best depending on whether the trickle vents were open or closed (with wind having a more important role when trickle vents were open). The best performing models at UTH were different to those found by previous authors. Sinden (1978) explored the ways the locations of leakage pathways affect the interaction of wind and stack effects. Variation in pathway locations may partially explain the difference in best performing models between previous literature and the trickle vents open and closed cases found at UTH.

While simple models of the effect of the ventilation driving forces worked well at UTH they did not perform well with the CS2 data. The wind data and the mechanical extract ventilation at CS2 are both likely to have contributed to this. The dwellings at CS2 were equipped with continuous MEV, in contrast to UTH which was naturally ventilated. If the MEV had generated pressure differences much greater than the natural driving forces then a nominally constant ventilation rate would have been expected, however the ventilation rate was highly variable. The models used in this research assumed a simple additive relationship between pressure difference arising from natural and mechanical causes, but these factors may interact in a more complex manner. For example, Nabinger and Persily (2008) found that the ventilation system 'competed' with the stack effect when temperature differences were positive, resulting in lower ventilation rates than if the system was switched off. Such effects would result in a poor fit with the models used in this research. However, the MEV was switched off at Flat B meaning that this flat was essentially naturally ventilated, but the models remained poor for this dwelling. The wind data used for CS2 came from a weather station 20 miles away, at Heathrow Airport, it is likely that this did not sufficiently represent the local wind conditions in the urban environment of CS2. The prevalence of urban dwellings in the stock means that understanding the effect of wind on ventilation in urban environments is important. Other research approaches, such as use of wind tunnels or modelling, are helpful for understanding the effect of wind in urban environments. However, it is currently uncommon that measurements of as-occupied ventilation rates in variable weather conditions are collected in sufficient volume for an analysis regarding the effect of weather conditions to take place. Such research would complement different research approaches, help to explore how the ventilation rates experienced in homes vary, and investigate the effect of this on exposure to pollutants and related health effects.

Although a clear relationship between the driving forces and the ventilation rates at

CS2 was not established, the results showed that the ventilation rates were almost always inadequate (less than 0.5 ach) if the windows were closed. The ventilation rates were also highly variable, windows closed ventilation rate results varied by over 0.5 ach in Flats C and D (only three windows closed results were measured in Flat A and Flat B had the ventilation system switched off). This was in contrast to the continuously delivered fan flow rates which were significantly above the rate required by ADF and taken by themselves would suggest adequate ventilation rates in the studied dwellings. This could have been caused either by air leaking through the ventilation ducts or due to the exhaust being close to an air inlet. Commissioning requirements for new ventilation systems require that fan flow rates are measured (HMG, 2010e), such measurements indicate a necessary condition has been met but are not sufficient to indicate a properly functioning ventilation system. It is unclear how frequently issues such as that identified at CS2 occur, further detailed research is required to understand how widespread this is.

Each of the participants at CS2 likely experienced significantly different ventilation rates during the times that they occupied their homes. The frequency with which the occupants opened their windows, both while present and absent was strikingly different, Flat A had at least one window open 80% of occupied time (98% of unoccupied time), whereas Flat D had at least one window open 5% of occupied time (0% of unoccupied time). It is therefore likely that the occupant of Flat D fairly frequently experienced inadequate ventilation rates while at home, whereas the occupants of Flat A usually experienced adequate ventilation. The extent to which this affected the IAQ the occupants experienced depends on the pollutant sources present over time. The species measured in the kitchens at CS2 did not breach WHO guidelines for IAQ at any point during the monitoring campaign.

Use of doors was shown make a difference to the ventilation rate at UTH. The mean ventilation rate measured in a single room at UTH with the door closed and trickle vents open was 0.3 ach (standard deviation 0.1 ach, N = 62), compared to a whole dwelling ventilation rate of 0.8 ach (± 0.1 ach, N=1). The results of a smoke survey indicated that air leakage paths were not uniformly distributed around the dwelling but were concentrated in the under stairs cupboard, around the services in the kitchen and bathroom, through several cracks in the walls and around the front door, this is similar to the findings of Stephen (2000). This suggests that the ventilation rates experienced by an occupant in different parts of the dwelling will not necessarily be well characterised by the whole dwelling ventilation rate. Further empirical research assessing the effects of using doors in occupied homes is required to investigate the prevalence and magnitude of such issues, but this finding suggests that greater attention should be given to the use of doors when considering IAQ and heat loss in occupied dwellings. There is little previous research addressing the use of doors in occupied homes, and although ADF requires an undercut beneath doors to allow airflow throughout dwellings (HMG, 2010b), in practice these are often smaller than required or missing (MHCLG, 2019b). The results from CS2 showed relatively little use of doors by the participants, although two dwellings were studio flats so this limited the capacity to explore door use. One of the participants always closed their bedroom door for sleeping, but it was not possible to measure the ventilation rate as they never left the dwelling unoccupied in this configuration. This highlights that the natural experiment research design has revealed insights into the way occupants use their homes, but was not able to quantitatively explore all scenarios. The use of experiments or agreement with occupants to test specific configurations would be valuable for future research to explore the effect of dwelling configuration on ventilation rates further. Such research would support efforts to ensure that ventilation systems are able to provide adequate ventilation given occupant use of doors.

At UTH the whole dwelling ventilation rate remained above 0.5 ach with the trickle vents closed. This meant that closing the trickle vents helped to avoid excessive ventilation and heat loss. In contrast, the single room ventilation rate fell from 0.3 ach (standard deviation 0.1 ach, N=62) to 0.2 ach (standard deviation 0.1 ach, N=39) on closing the trickle vents. This suggests that the appropriate position for the trickle vents depends on whether the internal doors are open or closed; further research is needed to assess the magnitude and prevalence of such issues in the stock. UTH was a very leaky dwelling so finding ventilation rates as low as 0.2 ach was surprising. This is important, both because trickle vents are known to be often closed in occupied dwellings (MHCLG, 2019b; Sharpe et al., 2015; Fox, 2008), and because many dwellings with trickle vents will be more airtight than UTH (Crawley et al., 2019) and may experience even lower ventilation rates. Moreover, dwellings such as UTH are likely to be retrofitted to improve their energy efficiency in the coming years and this will likely reduce ventilation rates further. This study therefore suggests that, depending on the occupant use of the building and the pollutant sources present, the combined use of internal doors and trickle vents may significantly impact IAQ. Further research is required to characterise this issue more widely in the stock.

7.3 Practices related to ventilation in homes

The final part of this work compared the assumed occupant actions implicit in ADF's description of ventilation systems to the participants' practices of manipulating the air in their homes. By considering how the participants influenced ventilation rates and requirements for ventilation in their homes from a Social Practice Theory (SPT) perspective, the ways in which the assumptions in ADF did and did not reflect the experience of living in and ventilating a home were revealed. There were several key findings and implications from this part of the work.

It is firstly important to note that there were several ways in which the ventilation system as-installed did not reflect the ventilation strategy or the design of continuous MEV systems in ADF, this affected the extent to which the participants' practices could align with ADF. The MEV as-installed had no boost flow rate which meant that extract ventilation as described in ADF was not possible in these dwellings. Moreover, the design intention according to the developers' drawings was that the boost flow rate would be triggered by a humidity sensor, this meant that there was no route through which the participants' could directly influence the flow rate of the MEV and that pollutants not associated with humidity would not be extracted. Additionally, although the purpose of extract ventilation in the ADF ventilation strategy includes local removal of pollution from continuous sources, the ventilation system described in ADF does not necessarily facilitate this. The described ventilation system provides extract ventilation in kitchens, bathrooms and utilities. While significant sources of pollution may often be located in these rooms there were several instances where this was not the case. These included mould growth in other rooms and the use of candles. The location of the ventilation extract in these cases would have resulted in pollutants from these sources spreading through the dwelling before being removed. It is challenging to design a ventilation system which is energy efficient and robust to unusual or unforeseen pollutant sources, but these issues highlight the limited flexibility in the system to deal with these. A partial solution could be to include manual switches as well as, or instead of, automatic control for boost ventilation.

The participants broadly shared meanings with the stated purposes of ventilation in ADF. For example, the participants had meanings associated with 'fresh' air in the home, keeping the air moving and limiting the spread of pollutants around the home. This suggests there may be social cues which the intended operation of ventilation technology and avoidance of indoor pollution could be aligned with. More research is needed to understand how to take advantage of this in designing ventilation systems which ultimately function as intended in occupied homes.

The participants often did not use the ventilation equipment in the manner intended. For example, none of the participants were aware that the trickle vents are intended to be permanently open and they were rarely used. Aspects of the participants' practices were aligned to ADF's extract ventilation (limiting the spread of pollutants around the building), but these necessarily used different technologies because the installed ventilation system did not have a boost flow rate. Doors were particularly important for the participants in this respect, although they were not much used at CS2, the participants had used them in previous homes for controlling the flow of smells, humidity and heat. The participants had no formal knowledge or rules regarding using the ventilation equipment or maintaining the ventilation equipment in the ways set out in ADF. Additionally, the participants had no clear practical understandings related to the continuous MEV, and this technology had been interpreted in various ways by different participants. These included: the isolation switch interpreted as only for the utility fan, the lack of cooking smells indicating the MEV worked well, perceived stuffiness indicating the system did not work well and the lack of noise from the system was a positive for some and a possible indication the MEV was not working for others. The participants lacked a direct verification or reassurance of what the MEV was for and whether it worked properly. The participants were not aware of having received manuals regarding the intended use or maintenance of the system as required by HMG (2010e), nonetheless research such as Southerton et al. (2011) and Baddeley (2011) suggests that only a very small proportion of people alter their actions after the simple provision of information. It is possible that changes to the design of ventilation technologies (including trickle vents and MEV) could encourage particular practical understandings regarding their use, without necessarily influencing the formal rules or knowledge dimension of the practice. Future research using appropriate methods and disciplines to test and investigate such approaches would be useful.

The participants and ADF did not always consider the same things to be pollutants. The case of candles and air fresheners is particularly striking as from the participant perspective these improved the indoor environment whereas from a technical perspective these reduced the air quality. ADF assumes occupants will purge ventilate in the event of high concentrations of pollutants, but the participants had almost no formal knowledge or rules regarding indoor pollutants and did not have practical understandings involving diluting these kinds of pollutants. Various organisations have advice for the public regarding indoor air pollution, for example Clean Air Day (Cleanairday.org.uk, 2020) and NICE (2020a), but so far these kinds of campaigns have not impacted the practices of the participants of this study. In contrast, the participants often had formal knowledge of outdoor pollution, which had been gained from a variety of sources including news, apps and public campaigns. Formal knowledge is only one element of a practice, and simply having knowledge is often not enough to change actions. Nonetheless, in the case of pollution caused by unscented or pleasantly scented products it seems likely that formal rules or knowledge will be important because direct perception is not possible. The lack of formal knowledge and practical understandings regarding limiting indoor pollutants from common sources suggests there is a need for better communication of the dangers and the practical steps people can take to reduce their exposure to indoor pollutants at home.

The participants' practices related to manipulating the air were much more nuanced than ADF's approach. The air in the home was shown to hold social significance for the participants. They took opportunities to manipulate the air to control the strength, timing and location of different smells within the home, such aspects reflect the remit of ADF. Further aspects of manipulating the air were associated with pleasant feelings of freshness, feelings of cleanliness and enjoyable connection to the outside world. The participants showed that it was not only compounds in the air which influenced their practices, but a broader range of factors played a role including temperature, noise and the quality of the outdoor air. As discussed in Chapter 2, previous research has identified that such issues influence what people do at home. Moreover, the technologies associated with the participants' practices were different to those outlined in ADF, in particular windows, doors and scented products featured prominently for the participants. By explicitly comparing the participants' practices with the assumptions in ADF the points of discrepancy have been made clearer; for example, unwillingness to purge ventilate in cold weather, or the desire to stop ingress of outdoor air while people smoke outside the building. Potential solutions might include manually controlled extract ventilation supporting increased ventilation rates in cold weather without requiring open windows, and a time-limited switch to stop mechanical ventilation in the case of external pollution. However, it would be useful to carry out further sociotechnical research to assess the appropriateness of any revisions to the planned ventilation system since it is challenging to balance the combined issues of energy use, adequate ventilation provision and occupant requirements.

7.4 Global discussion

The conclusions above relate to the results of each of the strands of work addressed in this research: measurement of ventilation in occupied homes, variation of ventilation rates in occupied homes and participant practices related to ventilation as compared to ADF intentions. This section discusses what can be learned by looking through these three windows together which could not have been seen by looking through any one window alone.

7.4.1 Inadequacy of ventilation rates with windows closed

Some of the complexities around adequate ventilation in homes have emerged. At CS2, the ventilation rates measured with all windows closed, the configuration in which ADF expects adequate ventilation to be provided due to the continuous MEV and trickle vents, were very often lower than 0.5 ach. As well as this, the results from the OSA showed that the amount of time the dwellings were occupied with all windows closed varied significantly, between 20% and 95% of occupied time and between 2% and 100% of unoccupied time. The IAQ occupants experience is related to pollutant sources and strengths and the ventilation rate during the time the occupants are present. These results indicate that the extent to which the these participants experienced adequate ventilation rates is strongly linked to the amount of time they had their windows open during occupied times, which was highly variable.

The results of the sociotechnical enquiry regarding the participants' ventilation-related practices began to explore the issues related to window use in these dwellings and some of the social reasons for different use of windows between the dwellings. The comparison of ADF intention with participant practices related to ventilation showed that windows are viewed extremely differently by the two entities. ADF's intention is that windows are used for purge ventilation during occasional circumstances in which high concentrations of pollutants are present. Sometimes the occupants used the windows in this manner; for example to dilute smells or smoke after burning food. However, the participants did not only use the windows for occasional and extreme events. For some of the participants window use was associated with a range of other practices in the home, such as getting up, getting ready to sleep, going out, hosting guests or cooking. For the participants, the specific smells detected in the home environment were sometimes highly socially significant and this had impacts on window use; most strikingly the fear of having a home that smelt of a pet dog drove very frequent window opening and air freshener use in Flat A. Furthermore, some participants had strong meanings related to wanting fresh air, removing stuffy air or wanting air to move or circulate, and they opened windows provide this. Such window opening was not related to particular events but rather associated with almost a sense that the dwelling itself was a source of continual pollution which needed to be diluted.

The quantitative results support some of the participants' interpretation that additional ventilation was often required when windows were closed. It is not clear to what extent the participants' perception that their dwellings were 'stuffy' or needed additional ventilation would have changed if the dwellings had higher ventilation rates when windows were closed (for example had the trickle vents been open); thus caution is required in interpreting these findings. However, trickle vents are known to be closed in many dwellings and MEV are commonly switched off (MHCLG, 2019b). It is notable that not all the participants had the sense that additional ventilation was needed when windows were closed, nor were there any robust indications for the participants that something needed to be done to increase the ventilation rate when windows were closed. In these flats the inadequate ventilation rates with windows closed mean that there is an unintended reliance on occupant perception to trigger window opening and increased ventilation rates. Such reliance may not deliver good IAQ because humans are not able to detect many harmful pollutants, such as carbon monoxide or radon, and others have pleasant scents, such as the various VOCs found in fragranced products (Steinemann, 2017; Shrubsole et al., 2019a).

The combination of different methods used were able to reveal the interactions between social and technical factors in relation to window use. A technical study alone could not have explored why some dwellings often have open windows and a social study alone would not have determined that ventilation actually was inadequate with windows closed. Even a socio-technical study which only measured fan flow rates would have mistakenly suggested that the ventilation rates with windows closed were adequate. Moreover, depending on the dwelling and time period studied, an average-based ventilation measurement could have made a similar error if it averaged over different window-opening configurations. This highlights the value of the repeated ventilation measurements used in this study.

7.4.2 Trickle vents as part of a ventilation strategy

The results from UTH showed possible technical issues with trickle vents: inadequate ventilation rates were recorded in the single room with the door shut, while excessive whole house ventilation rates were measured with all doors open. Several other studies have found inadequate ventilation rates in dwellings provided with trickle vents and have found that trickle vents are often closed in occupied dwellings (Sharpe et al., 2015; MHCLG, 2019b). The results at CS2 showed that there were inadequate ventilation rates with trickle vents and windows closed. While it was not possible to determine whether open trickle vents would have resulted in adequate ventilation rates, the qualitative investigation of the participants' practices gave several important insights regarding the use of trickle vents.

ADF states that 'trickle ventilators are intended to be normally left open' (HMG, 2010b, p. 15), however they were rarely open in the dwellings studied at CS2. The trickle vents are intended to provide an inlet through which the continuous MEV equipment can draw air in, so the closure of trickle vents prevents this ventilation system from operating as planned. Although some of the participants broadly understood that the trickle vents provided a small air inlet, none knew that these were designed to work in collaboration with the MEV. In most circumstances that the participants wanted outdoor air trickle vents were not felt to be the most appropriate conduit and windows were used instead. Indeed, three participants had never noticed or did not know the purpose of their trickle vents; windows were the only known technology available to control the ventilation in their homes. When trickle vents were used, this was associated with conditions indicating outdoor air was needed intersecting with security concerns. For example, on occasion Aaron opened trickle vents before closing windows and leaving for a holiday. In a previous home Darren had always open trickle vents: he perceived this dwelling to be airtight since it was warm and he noticed smells lingering, he therefore felt that additional airflow was permanently required and so opened the trickle vents. Despite this, he had not noticed the trickle vents in his flat at CS2; none of the conditions (temperature, smells) indicated to him that there could be low ventilation rates in his flat. This relates an issue raised in Section 7.4.1: people are known to be unreliable sensors of poor IAQ and in these flats the unintended reliance on individuals' senses does not necessarily result in adequate ventilation rates.

Many new dwellings have been built on the assumption that adequate ventilation will be provided through open trickle vents, but they are known to often be closed in practice

(Sharpe et al., 2015; MHCLG, 2019b). The results of this research have shown that there is an important social context; participants did not interpret trickle vents as being intended to be always open, instead that they should only be open in specific circumstances. Further research would be useful to understand what interventions (for example possible changes to design or effective communication strategies) could be used to embed open trickle vents as the norm. This is likely to also be an issue in retrofitted homes, for which it is required that occupants are given advice regarding their use of ventilation equipment (BSI, 2019). Research to investigate the best forms of advice in this context would be useful. A further factor complicating the design of robust ventilation strategies in occupied homes was raised by the results at UTH suggesting that the configuration of doors and windows may have a significant impact on the adequacy of ventilation, including affecting whether opening trickle vents is advisable. The next section addresses this further.

7.4.3 Use of doors in occupied dwellings

The results from UTH also showed that how occupants' use doors may significantly influence the ventilation rates they experience. There was a significant difference between single room and whole house ventilation rates at UTH. It was not possible to obtain further experimental results related to this at CS2 since doors were almost always open during unoccupied periods, although the measured configurations often represented those most prevalent during occupied times. Undercuts beneath doors are required by ADF to ensure adequate airflow through the dwelling when doors are closed. Unfortunately, in practice, undercuts are not always as large as required, including at UTH and CS2 and as found by research such as MHCLG (2019b). Furthermore, the qualitative results indicated that undercuts were sometimes blocked if participants noticed excessive cold draughts.

Use of doors was found to be socially significant. The participants all had clear meanings around the use of doors for ensuring appropriate privacy, particularly bedroom doors at night if sharing a house with others. Conversely, opening doors was associated with having the right atmosphere at home, or with friendly communication with housemates. Doors were sometimes used to facilitate different environmental conditions in different parts of the home. For example, doors were closed during cooking to keep food smells confined to, or excluded from, particular rooms, or were closed when particular windows were open to keep cooler temperatures in particular spaces.

The results from UTH have illustrated the technical issue in one test house, and the results from CS2 have shown that the social dimension related to doors is significant. This suggests that designing and regulating for ventilation systems which are robust to occupant door use may be challenging. There has been little research addressing this issue and further research using physical, modelling, social and sociotechnical research approaches would be useful to understand the use of doors and how this might affect experienced IAQ, or heat loss from occupied rooms. Such research could point to ways that door use might be encouraged or discouraged to support better IAQ or energy use in buildings.

7.4.4 Lack of fail-safe operation of the ventilation system

There was no obvious route through which occupants might be expected to notice if their MEV was off or to recognise that the system should be on all the time. The median ventilation rate in Flat B (where the MEV was switched off) with windows closed was 0.24 ach, significantly lower than 0.42 ach for the other studio flat in which the system was usually switched on. Additionally, Brandon (the occupant between June and September) frequently burnt candles while at home, potentially meaning that significant pollutants were released, although he very often had open windows so this will have increased the ventilation rate. Brandon was completely unaware of the MEV system, whereas Bridget (the occupant between September and January) recognised that the ceiling terminals were associated with ventilation but had never checked the system was on. The occupants of the other flats had varying interpretations of the MEV system and whether it should be on or off. Cal was very aware of the system and deliberately switched it off when leaving for holidays and back on when he returned. Conversely, Aaron and Alice thought the isolation switch for the whole system only controlled the utility cupboard fan, they permanently left the switch on as they believed this was important for the washing machine thus inadvertently ensuring that the MEV system for the whole flat was operational.

The Domestic Ventilation Compliance Guide (DVCG) (HMG, 2010e) requires that end users are provided with information on the intended operation of the ventilation system, however the occupants were not aware of any manuals or having received any advice regarding the operation of their ventilation systems. These provisions have not resulted in these ventilation systems becoming embedded in the participants' practices such that the equipment is used in the intended manner. As noted above, previous research has found that simple information provision is unlikely to induce changes in people's actions (Baddeley, 2011; Southerton et al., 2011); future research investigating strategies to improve the use of ventilation systems in occupied homes would be beneficial.

Finding the MEV system switched off in one of the flats and little occupant knowledge of the systems highlights the lack of contingency for improper operation or failure of the system. Trickle vents are often closed in dwellings, occupants may switch off mechanical ventilation or it may malfunction. In these scenarios it may be difficult for occupants to detect any subsequent changes in IAQ, or to diagnose which technology is not performing as it should. Future research could explore whether these ventilation systems could be installed with technology that is fail-safe or provides feedback to the occupant. For example, Scottish building regulations require that newly built dwellings are provided with CO_2 sensors in the main bedroom in an attempt to provide meaningful feedback to occupants and encourage them to take actions to ventilate their home when necessary (BSD, 2017). Such technologies may mitigate the risk of inadequate IAQ in dwellings with purpose provided ventilation.

The current lack of routes for checking the functioning of the system and the limited extent to which the intended function of ventilation systems is embedded in the occupants' practices may mean that either the dwelling suffers from low ventilation rates (as observed in Flat B), or that the occupants employ greater use of the windows if the dwelling is perceived to have inadequate air quality. Increased window use in winter could negate the carbon-savings associated with increasing the airtightness of such dwellings so future research regarding occupant interactions with the dwelling and ventilation technologies would support the decarbonisation of the built stock, whilst ensuring healthy living conditions.

7.4.5 Unknown cleaning and maintenance requirements of ventilation systems

DVCG (HMG, 2010e) requires that information is provided to end users regarding cleaning and maintenance of ventilation systems. The manufacturers of the MEV equipment installed in CS2 did not give recommendations regarding maintenance in their manual (Vent-Axia, 2020). Cleaning the extract terminal in the bathroom in Flat C resulted in almost doubling the flow rate through this terminal. It is not known how much this affected the whole dwelling ventilation rate since this occurred at the end of the monitoring period. However, such changes to the flow rate could make significant differences to the delivered ventilation rates. The maintenance requirements for the trickle vents installed at CS2 could not be found, but another trickle vent product from the same company recommended removing dust (Greenwood, 2003). At CS2, there was visible dust inside the trickle vents, which could reduce their effective area. Previous research has noted that background ventilators have been found in poor condition in occupied homes (Sinnott, 2016; Fox, 2008), but such studies have not quantified the effect of this. Given the prevalence of trickle vents in dwellings and other buildings this is an important area for further research.

Only one of the participants showed an interest in the maintenance of the ventilation system. This participant had a meaning associated with cleaning visible dust around the ventilation terminal. He had wanted to clean this for some time but its location on the ceiling meant that it was not possible until the author brought step-ladders to his flat; he had lacked appropriate technologies for carrying out the cleaning. Although ADF recommends that ventilation systems are installed in such a way as to facilitate cleaning, in practice this occupant still found the location of the terminals difficult to reach. The current information provision strategy required by HMG (2010e) appears to be insufficient for ensuring maintenance of these systems is carried out. Gilbert (2014) analysed data from ventilation manufacturers in the UK and noted there there are no large scale maintenance schemes for residential ventilation systems, and that the volume of sales of replacement MVHR filters indicates that maintenance is not being carried out for a large number of such systems; this suggests that domestic ventilation systems are unlikely to be maintained. Inadequate maintenance could result in significant implications to health, cost and expected carbon-savings associated with these technologies, further research is required to explore the issues raised more widely in the stock.

7.4.6 Reflecting on the combination of methods

It is striking that very little of the discussion in this section would have been possible if only technical or only social research methods had been applied. Applying one approach throughout the study would have allowed a deeper exploration of the issues pertinent to that particular discipline. For example, completely leaving out the social side of the research could have allowed comparison between commercially available modelling softwares like CONTAM or EnergyPlus with the empirical results. Such a comparison could have explored the extent to which the empirical results could be predicted and how the occupant use of windows and doors could be modelled. However, no amount of technical research could have helped to give an idea about why the ways that ADF imagines ventilation to happen do not happen in practice. Conversely, without the technical measurements to support the social research it would not have been clear that the occupants actually do frequently experience inadequate ventilation rates with windows closed and so it would have been easy to ‘blame’ the participants for their frequent window use.

Much of the currently reported research relating to ventilation and IAQ takes a single disciplinary approach, but the there is much to be learned through research which combines different approaches (Shrubsole et al., 2019b). Ventilation in occupied homes is intertwined with technical and social considerations and addressing both in ventilation research can help to provide deeper understandings. Similarly, the solutions for providing adequate ventilation in homes will also need to address both aspects.

7.5 Conclusions

This work explored the measurement, variability and sociotechnical nature of ventilation in occupied homes. The first part developed an analysis method such that the CO_2 decay technique could be applied in extended monitoring campaigns to explore ventilation variation in occupied homes. This involved the development of the occupancy status algorithm (OSA), and an analysis algorithm which identified CO_2 decays complying with requirements regarding spatial homogeneity, static outdoor CO_2 concentrations and a maximum of decay time of 90 minutes. Uncertainties associated with the measurements were characterised, with quantifiable uncertainties between 9% and 13% for the studied dwellings. The second part of the research investigated the variability of ventilation in an unoccupied test house and four occupied dwellings. These showed the potential impact of simple occupant actions on ventilation rates experienced in homes. Finally, a Social Practice Theory framework was used to explore participants’ practices related to ventilation and to compare these to the planned ventilation strategy and system described in ADF (HMG, 2010b). This revealed points of tension between the technical expectations regarding ventilation described in ADF and the ways the participants manipulated the air in their homes. Although this research took place in an English context, many of the issues regarding the measurement, variability and sociotechnical nature of ventilation in homes is likely to transfer to other contexts.

This research highlights the complexity of ventilation in occupied homes and the consequent difficulty in ensuring regulation results in adequate ventilation. Ventilation in homes is a socio-technical system, this research highlighted particular discrepancies between ventilation as described in ADF and how the participants' manipulated the air in their homes. The participants did not always use the provided technologies in the intended manner; trickle vents were almost always closed and continuous MEV had sometimes been switched off, such findings are not unique (MHCLG, 2019b; Sharpe et al., 2015). Although occupants are supposed to receive guidance regarding the operation and maintenance of ventilation equipment (HMG, 2010e) in these cases such guidance has not resulted in the intended operation. These findings raise an issue regarding how best to encourage the intended use of such technologies. Additionally, the regulations assume occupants will ventilate in the event of significant loads of pollution, but in some cases what the participants considered desirable was technically a pollutant. The participants had little formal knowledge of indoor pollutant sources and only perceived a problem when pollutants either smelt badly or caused direct and tangible health effects. This is important given that many indoor pollutants either have no smell or are pleasantly scented. Further research regarding effective means to encourage occupants to increase ventilation rates or remove sources when appropriate would be useful. Finally, research related to IEQ addresses a wide range of factors important to occupant comfort (Frontczak and Wargocki, 2011), and these participants responded to a wide range of conditions in their interactions with the air and ventilation technologies, for example the social significance of particular smells, thermal comfort, noise, outdoor pollutants and pleasant connections to the outside world. Moreover, the high degree of variability of ventilation rates with weather and simple occupant actions such as door use and trickle vent use has been underlined. Such physical findings further compound the challenge of providing robust ventilation systems in occupied homes. Further research is needed to investigate how ventilation systems could be better designed to ensure adequate ventilation is provided while allowing flexibility given the multifarious conditions arising in occupied homes.

Ventilation systems which provide adequate ventilation rates in homes as-occupied are increasingly important given the need to rapidly decarbonise (UNFCCC, 2015), and the significant heat loss associated with ventilation (CIBSE, 2015). This is resulting in increasingly airtight buildings which rely on mechanical systems to provide ventilation (Crawley et al., 2019). Adequate ventilation in such buildings is essential given the relationship between ventilation, IAQ and health (Shrubsole et al., 2019b). Further research regarding the ventilation rates achieved in occupied dwellings will support efforts to improve conditions in newly built and retrofitted homes, deliver energy savings and provide healthy indoor environments.

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Appendix A

Participant information and informed consent documents

The participant information sheet and informed consent forms given to the participants are reproduced on the following pages.

Information Sheet for Participants in Research Studies

You will be given a copy of this information sheet.

Title of Project: Understanding Ventilation in Occupied Case Study Dwellings

This study has been approved by the UCL Energy Institute Research Ethics Coordinator.

Researcher Name	Jessica Few
Address	Bartlett School of Environment, Energy and Resources Faculty of the Built Environment Central House, 14 Upper Woburn Place London, WC1H 0NN
Email Address	[redacted]
Phone Number	[redacted]

We would like to invite to participate in this research project.

Details of Study

Overview. This project aims to further our understanding of airflow in occupied homes which are built in accordance with the latest building regulations.

Recruitment. I am seeking participants for this PhD project. Participants would be interviewed and sensors would be placed in their homes.
If you are not the only person living in your home, then all the people living there need to read this information sheet. If you agree to take part in the research, then all of you need to sign an informed consent form.

What it would mean for you. A colleague and I would visit your home to install several different sensors. A combined CO_2, temperature and relative humidity sensor would be placed in all rooms, these sensors need to be plugged in (we will bring extension plugs so you don't lose socket space). An indoor air quality sensor would be placed in either the kitchen or the living room. This sensor needs to be plugged in and makes a small fan noise. Sensors would also be placed on some doors and windows to determine when they are open (these sensors do not need to be plugged in).

All sensors would be placed on shelves or tables or attached to the wall, doors or windows using Command strips. Command strips are adhesive strips which are designed to be removed without making a mark. It is very unlikely, but possible, that the Command strips could cause a small amount of damage to the wall when they are removed.

In all cases, there are several constraints on where the sensors can be placed, but your permission would be sought and you can refuse the suggested placement of any sensors. Once the sensors are in place they should not be moved for the duration of the study. Please contact me if they are causing an inconvenience.

The equipment would take up to two hours to install and a further hour to remove at the end of the project. Following this, occasional visits to your house (at most, once every two months) would be made to take the data from the sensors, this would take less than 20 minutes. In all cases, the timings of these visits would be agreed in advance. The sensors would be in place until next winter.

A colleague and I would carry out a test to measure the airtightness of your home. This would involve placing a canvas doorframe in your front door frame and using a fan to measure the air flowing into the house. This would take up to one hour.

You would also be interviewed about your thoughts and opinions on your home and how you use it. This interview would take approximately one hour and would take place in your home in winter. Once the interview has started you would be free to decline to answer any of the questions or to stop the interview at any time. The interview would be audio-recorded and then I would transcribe it, after transcription the original audio would be deleted.

Photographs would be taken in support of the project, but these would not include personal items unless you agree that this is acceptable (curtains, cushions, furniture etc.). Photographs from which your house could be identified will not be taken (street signs, door number etc.). You will be given the opportunity to review and delete any photographs that are taken.

At the end of the project I would provide you with a plain English summary of the findings, along with the final PhD thesis if you would like to see it. I would also be available to discuss the findings with you in further detail if you would like. This research could identify times and or rooms where the ventilation rate is below what is considered an adequate level by the building regulations, this information would be highlighted to you.

What I would know from the data. I would know the CO_2, temperature and relative humidity in the rooms of your house and would know when different doors and windows are open. By combining these data I would be able to see when your house is occupied and (possibly) which room is occupied. This would help me understand the airflow measurements. It would not be possible and is not of interest to identify your activities apart from room occupancy.

It would be possible to find out when the ventilation rate is too low to keep CO_2 and/or humidity within recommended guidelines. I would share this information with you.

Choosing whether to participate. It is up to you to decide whether to take part or not; choosing not to take part will not disadvantage you in any way.
There is no pressure to participate if you do not want to. You do not need to give me a reason if you would prefer not to participate.
If you do decide to take part you are still free to withdraw at any time and without giving a reason.
If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

Further information. Please discuss the information above with others if you wish, or ask us if there is anything that is not clear or if you would like more information. If you have further questions later, please contact me.

Complaints. If this study has harmed you in any way or if you wish to make a complaint about the conduct of the study you can contact UCL using the details below for further advice and information:
Dr. Cliff Elwell
Address: Central House, 14 Upper Woburn Pl, Bloomsbury, London WC1H 0NN
Phone [redacted]
Email: [redacted]

Data Protection Privacy Notice

All information from which you or your house could be identified will be removed from any discussion of the project and in any publication of the findings.
After the data has been fully anonymised, it would be published in accordance with EPSRC guidance. If you wish, you can see a copy of this before it is published.

Notice: The data controller for this project will be University College London (UCL). The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk. UCL's Data Protection Officer can also be contacted at data-protection@ucl.ac.uk.

Further information on how UCL uses participant information can be found here:

https://www.ucl.ac.uk/legal-services/privacy/ucl-general-research-participant-privacy-notice

Your personal data will be used for the purposes outlined in this notice. The categories of personal data used will be as follows:

Name
Address
Telephone number

The legal basis that would be used to process your *personal data* will be performance of a task in the public interest.

Your personal data will be processed so long as it is required for the research project, which is until October 2020. If we are able to anonymise or pseudonymise the personal data you provide we will undertake this, and will endeavour to minimise the processing of personal data wherever possible.

You have certain rights under data protection legislation in relation to the personal information that we hold about you. These rights apply only in particular circumstances and are subject to certain exemptions such as public interest (for example the prevention of crime). They include:

- The right to access your personal information;
- The right to rectification of your personal information;
- The right to erasure of your personal data;
- The right to restrict or object to the processing of your personal data;
- The right to object to the use of your data for direct marketing purposes;
- The right to data portability;
- Where the justification for processing is based on your consent, the right to withdraw such consent at any time; and
- The right to complain to the Information Commissioner's Office (ICO) about the use of your personal data.

If you are concerned about how your personal data is being processed, or if you would like to contact us about your rights, please contact UCL in the first instance at data-protection@ucl.ac.uk.

If you remain unsatisfied, you may wish to contact the ICO. Contact details, and further details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

Thank you for reading this information sheet and for considering take part in this research.

Informed Consent Form for Participants in Research Studies

Please complete this form after you have read the Information Sheet.

Title of Project: Understanding Airflow in Occupied Case Study Dwellings

This study has been approved by the UCL Energy Institute Research Ethics Coordinator.

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you.

If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you to decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

I confirm that I understand that by ticking/initialling each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

Participant's Statement

1.	I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction.	
2.	I consent to participate in the study.	
3.	I understand that if I decide at any time that I no longer wish to take part in this project, I can notify the researchers involved and withdraw immediately.	
4.	I consent to the use of my personal data (name, address and phone number for arranging equipment installation and interview) for the purposes of this research. I understand that it will be treated as strictly confidential (only shared with the research team), will be securely stored and will be handled in accordance with Data Protection legislation.	
5.	I consent to an audio recorded interview and understand that the recordings will be destroyed immediately following transcription.	
6.	I agree that my data, after it has been fully anonymised, can be shared with other researchers	
7.	I am aware of who I should contact if I wish to lodge a complaint.	

Signed:

Date:

Appendix B

Interview guides

The interview guides used for all interviews at CS2 are reproduced on the following pages.

<table>
<tr><td colspan="4">Introduction and Consent

Thank you for taking part in my research. I’ll start by asking you some general questions about your home, and then some more specific questions about the air in your home, and then at the end it would be great if we could walk around the house together and you could show me a few of the things we’ve talked about, like the windows, doors and fans in the house. If I ask about anything you don’t want to talk about, you can just tell me you’d rather not go into it. There aren’t any right or wrong answers to any of the questions, I’m just really interested in how you interact with the building.

So if you agree I’ll record our conversation on the voice recorder – it won’t be listened to by anyone other than me and my supervisor and will be completely confidential, so I won’t share your name or address with anyone, I might use quotes in written reports but these will be completely anonymous.

Does that sound ok, are you happy to go ahead?</td></tr>
<tr><td colspan="4">Background</td></tr>
<tr><td colspan="4">So, how long have you lived here?</td></tr>
<tr><td colspan="4">And, do you own the flat, or is it privately rented, or…?</td></tr>
<tr><td colspan="4">And, can you tell me about why you chose to live here?</td></tr>
<tr><td colspan="4">And how does this flat compare to your previous home? Are there things you particularly like or dislike in comparison?</td></tr>
<tr><td colspan="4">Ok, and in an average week, what’s your typical schedule like in terms of how much you’re at home? And, what kinds of things do you mostly spend your time doing when you’re here?</td></tr>
<tr><td colspan="4">Can I ask if you smoke? How much? Where?</td></tr>
<tr><td colspan="4">Thermal comfort and temperatures</td></tr>
<tr><td colspan="4">Could you tell me about the temperature in the flat?</td></tr>
<tr><td>Summer?</td><td>Winter?</td><td>Times of day?</td><td>Easy or difficult to stay right temperature?</td></tr>
<tr><td colspan="4">Air quality and Ventilation</td></tr>
<tr><td colspan="4">I’m interested in what you think about the air in the flat…?</td></tr>
<tr><td>Stuffy / fresh / smells / humid?</td><td>Different areas?</td><td>Different seasons?</td><td>Times of day?</td></tr>
<tr><td colspan="4">Could you tell me about circumstances in which you’ve noticed the air in the flat being particularly good?</td></tr>
<tr><td>What was good?</td><td>Do when it was like that?</td><td>Other times?</td><td>Other places?</td></tr>
<tr><td colspan="4">Could you tell me about circumstances in which you’ve noticed the air in the flat being particularly bad?</td></tr>
<tr><td>What was bad?</td><td>Do when it was like that?</td><td>Other times?</td><td>Other places?</td></tr>
<tr><td colspan="4">How does the air seem after you’ve been away?</td></tr>
<tr><td colspan="2">How do you feel about that?</td><td colspan="2">Do you do anything to try to change it?</td></tr>
</table>

<table>
<tr><td colspan="12">Ok, and then how do you like the air to be in the flat?</td></tr>
<tr><td colspan="12">Do you ever get condensation?</td></tr>
<tr><td colspan="3">Why?</td><td colspan="3">Where?</td><td colspan="3">Do you do anything about it?</td><td colspan="3">Anything else cause it?</td></tr>
<tr><td colspan="12">In your opinion, is it easy or difficult to get rid of smells and humidity in the kitchen and bathroom?</td></tr>
<tr><td colspan="3">Anything you do to get rid of them?</td><td colspan="3">Does that work well?</td><td colspan="3">Other rooms?</td><td colspan="3">Smells travel around the house?</td></tr>
<tr><td colspan="12">Do you find that air lingers in any areas?</td></tr>
<tr><td colspan="6">Do those areas feel different?</td><td colspan="6">Do you do anything to try to change that?</td></tr>
<tr><td colspan="12">Do you ever find there are circumstances where you need fresh air in the flat?</td></tr>
<tr><td colspan="3">Why?</td><td colspan="3">How would you do that?</td><td colspan="6">What’s different / desirable about the outdoor air at those times?</td></tr>
<tr><td colspan="3">Would you do things differently at different times?</td><td colspan="3">Times of the year? Or times of day?</td><td colspan="6">What about other rooms?</td></tr>
<tr><td colspan="12">When it’s cold outside, do you ever find there’s too much cold air coming in?</td></tr>
<tr><td colspan="6">Coming from where?</td><td colspan="6">What do you do?</td></tr>
<tr><td colspan="12">And, is there anything else you do to affect the air in the flat?</td></tr>
<tr><td colspan="12">Or anything else to clean the air?</td></tr>
<tr><td colspan="12">I wondered what your opinion is of the outdoor air quality here?</td></tr>
<tr><td colspan="6">Does that change anything you do inside?</td><td colspan="6">Do you notice any changes over the day or year?</td></tr>
<tr><td colspan="12">And what about indoor air quality?</td></tr>
<tr><td colspan="4">Is that ever an issue?</td><td colspan="4">Causes?</td><td colspan="4">Anything you do?</td></tr>
<tr><td colspan="12">And, could you tell me, is there a ventilation system here? And how does it work?</td></tr>
</table>

Walk through
Ok, that’s great, could we go through the house and look at a few things together?

Maybe we can start with the windows…			
We talked about X, are there other circumstances they would be used?	Different times of day? Different seasons?	How much would you open them?	Different rooms? Kitchen, bedroom, living room.
What about closing them, what circumstances?	Different times of day? Different seasons?	Winter when the heating is on?	Different rooms? Kitchen, bedroom, living room
In previous places, have you used windows in a similar way?	What was different about how you used them?	What was different about the circumstances you’d use them in?	Why did you use them differently?

Have you ever had advice about opening or closing the windows?		
What was the advice?	Where from?	Do you follow it?

What’s the thing at the top of the frame?			
Tried to do anything with it?	Or find out about it?	Why / why not?	Other rooms?
Advice about what it is?	What advice?	Where from?	Do you follow it?
Have those been in other places you’ve lived / know?	How did you use them / others use them there?	What for?	Why?

Ok cool, and then could you show me the cooker hood?		
We talked about X, are there other circumstances you’d use it?	What do you think about it? Effective / noisy?	Anything stop you using it?
Advice about using it? What? Where from? Follow?	Does it ever need any maintenance?	Any other circumstances you’d use it?
In other places you’ve lived / know?	How did you use them there?	Why different / same?

Are there any other fans in the kitchen (boost)?		
We talked about X, other circumstances?	What do you think about it? Effective / noisy?	Anything stop you using it?
Advice about using it? What? Where from? Follow?	Does it ever need any maintenance?	Any other circumstances you’d use it?
In other places you’ve lived / know?	How did you use them there?	Why different / same?

And, is there a fan in the bathroom? Could you show me that too?		
We talked about X, other circumstances?	What do you think about it? Effective / noisy?	Anything stop you using it?

Advice about using it? What? Where from? Follow?	Does it ever need any maintenance?	Any other circumstances you'd use it?
In other places you've lived / know?	How did you use them there?	Why different / same?
Ok, and then you've got internal doors, this one is open / closed now		
We talked about X, other circumstances would you close it?	Different times of day?	Times of week or year?
In other places you've lived / know?	How did you use them there?	Why different / same?
What about the other doors in the flat?	Living room, bathroom, bedroom.	Any advice about using internal doors?
I think there's a bit of a gap at the bottom of the door.. what do you think of that?		
When we were walking around I noticed this fan / dehumidifier / candle etc, could you tell me about that?		
Closing		
That's great, thanks so much for showing me around and answering those questions!		
Is there anything else you'd like to mention about what it's like living here?		
Can I also ask how you've found the experience of being involved with the research so far?		
How have you found it having the sensors in your flat?		
Is there anything else you'd like to ask me before we finish the interview?		

Appendix C

Ventilation rates and weather conditions during measurement periods and occupied periods.

The figures on the following pages present the measured ventilation rates measured, weather conditions during occupied and measurement periods for the four most common configurations of doors and windows in Flats A, C and D at CS2. The equivalent figure for Flat B was presented in the main body of the thesis, Figure 5.10.

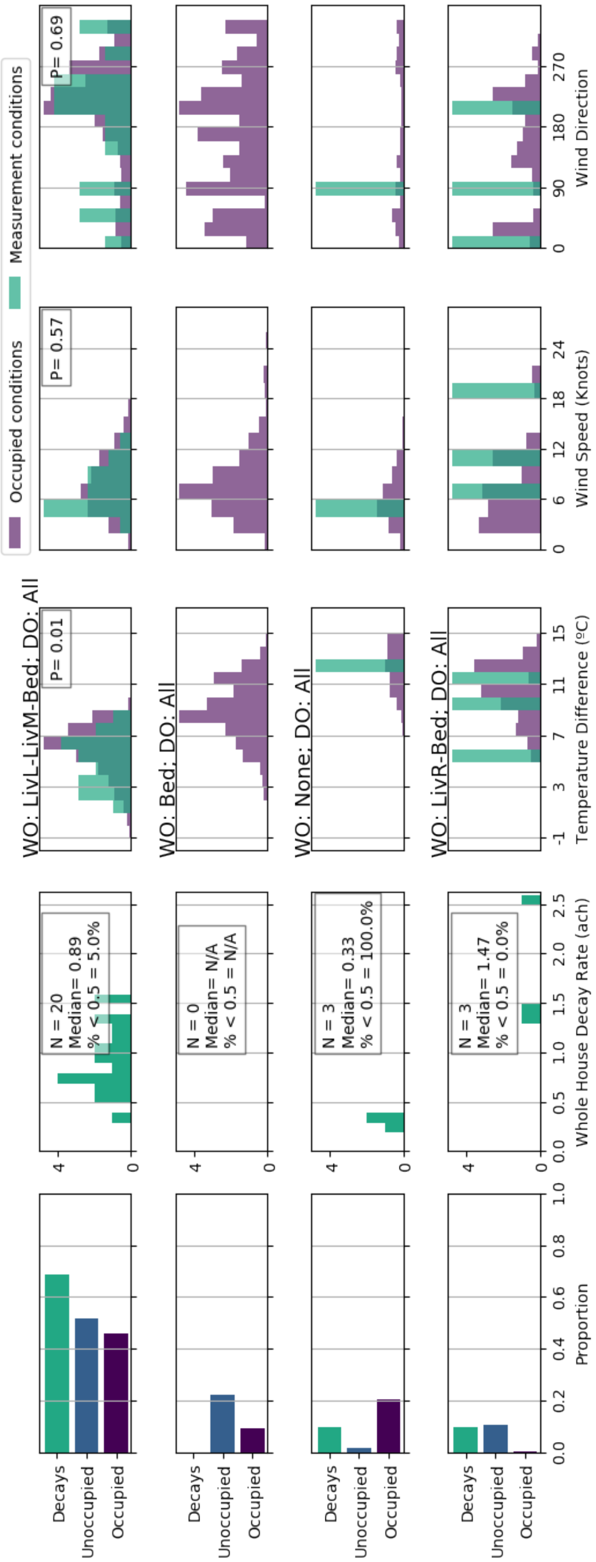

Figure C.1: Results for the four most common configurations of doors and windows from Flat A at CS2. For each configuration the proportion of measurements, unoccupied time and occupied time recorded is shown in the left figure; the distribution of measured ventilation rates in the second left figure; the distribution of temperature differences, wind speed and wind direction during occupied and ventilation measurement periods and the p-value from the Mann-Whitney U-test are shown in the final three plots.

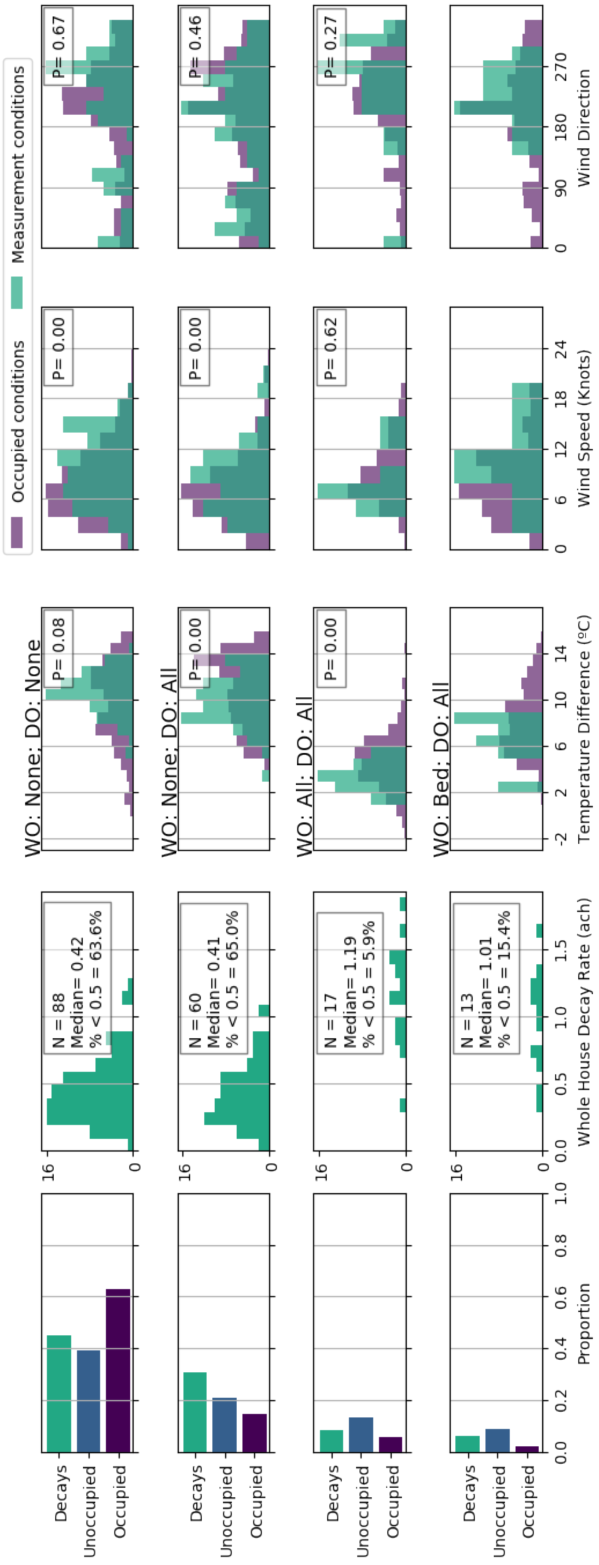

Figure C.2: Results for the four most common configurations of doors and windows from Flat C at CS2. For each configuration the proportion of measurements, unoccupied time and occupied time recorded is shown in the left figure; the distribution of measured ventilation rates in the second left figure; the distribution of temperature differences, wind speed and wind direction during occupied and ventilation measurement periods and the p-value from the Mann-Whitney U-test are shown in the final three plots.

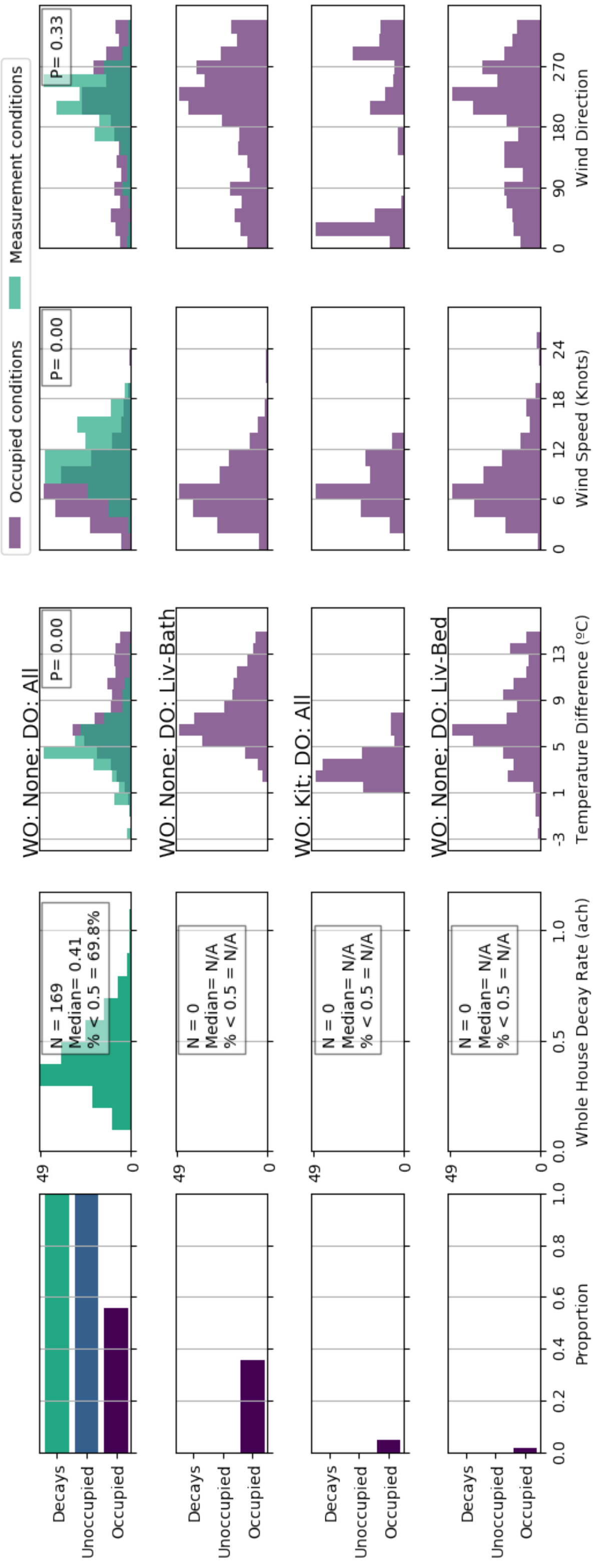

Figure C.3: Results for the four most common configurations of doors and windows from Flat D at CS2. For each configuration the proportion of measurements, unoccupied time and occupied time recorded is shown in the left figure; the distribution of measured ventilation rates in the second left figure; the distribution of temperature differences, wind speed and wind direction during occupied and ventilation measurement periods and the p-value from the Mann-Whitney U-test are shown in the final three plots.

Appendix D

Full ventilation rate results for CS2

Tables D.1 to D.4 give all ventilation rates measured for the flats at at CS2, along with the combined uncertainty, weather conditions and the configuration of doors and windows during the measurement period.

Table D.1: Results for Flat A at CS2: measured ventilation rates and their uncertainty, temperature difference, wind conditions and the configuration of doors and windows during the measurement time. See Table D.5 for a key of the abbreviations used in describing the door and window configurations.

Ventilation rate (ach)	Combined uncertainty (ach)	T_{in} - T_{out} (ºC)	Wind speed (knots)	Wind direction (º)	Door and window configuration
0.63	0.09	7.1	4.0	120	WO: All DO: All
1.27	0.03	7.4	3.0	150	WO: All DO: All
0.34	0.12	6.0	4.5	82	WO: LivWLHLivWMBedW DO: All
0.54	0.06	2.9	12.0	210	WO: LivWLHLivWMBedW DO: All
0.57	0.07	6.8	2.6	14	WO: LivWLHLivWMBedW DO: All
0.61	0.09	6.1	7.0	210	WO: LivWLHLivWMBedW DO: All
0.62	0.03	-4.6	10.2	150	WO: LivWLHLivWMBedW DO: All
0.74	0.06	7.3	9.5	91	WO: LivWLHLivWMBedW DO: All
0.74	0.09	2.5	6.0	220	WO: LivWLHLivWMBedW DO: All
0.76	0.14	6.6	8.1	213	WO: LivWLHLivWMBedW DO: All
0.79	0.17	5.7	5.9	241	WO: LivWLHLivWMBedW DO: All
0.82	0.13	4.4	4.0	160	WO: LivWLHLivWMBedW DO: All
0.97	0.04	7.7	4.2	45	WO: LivWLHLivWMBedW DO: All

0.99	0.18	3.5	6.0	330	WO: LivWLHLivWMBedW DO: All
1.08	0.05	8.5	5.5	45	WO: LivWLHLivWMBedW DO: All
1.09	0.07	3.0	5.6	330	WO: LivWLHLivWMBedW DO: All
1.12	0.18	1.4	5.6	187	WO: LivWLHLivWMBedW DO: All
1.20	0.11	3.4	7.4	252	WO: LivWLHLivWMBedW DO: All
1.36	0.18	4.2	8.0	250	WO: LivWLHLivWMBedW DO: All
1.37	0.11	6.5	7.0	223	WO: LivWLHLivWMBedW DO: All
1.53	0.10	2.9	12.0	220	WO: LivWLHLivWMBedW DO: All
1.54	0.15	5.3	8.3	286	WO: LivWLHLivWMBedW DO: All
0.44	0.16	8.8	13.1	87	WO: LivWRH DO: All
1.38	0.10	11.0	8.0	10	WO: LivWRHBedW DO: All
1.47	0.09	9.4	11.0	90	WO: LivWRHBedW DO: All
2.52	0.19	5.9	19.3	210	WO: LivWRHBedW DO: All
0.28	0.04	12.7	4.9	94	WO: None DO: All
0.33	0.05	12.6	5.1	97	WO: None DO: All
0.34	0.04	12.9	4.0	95	WO: None DO: All

Table D.2: Results for Flat B at CS2: measured ventilation rates and their uncertainty, temperature difference, wind conditions and the configuration of doors and windows during the measurement time. See Table D.5 for a key of the abbreviations used in describing the door and window configurations.

Ventilation rate (ach)	Combined uncertainty (ach)	T_{in} - T_{out} (ºC)	Wind speed (knots)	Wind direction (º)	Door and window configuration
0.66	0.06	4.0	5.5	245	WO: All DO: All
0.71	0.03	3.5	12.1	208	WO: All DO: All
0.92	0.04	0.7	11.5	303	WO: All DO: All
1.01	0.15	-0.5	9.0	180	WO: All DO: All
1.01	0.04	4.9	6.0	220	WO: All DO: All
1.15	0.05	5.6	5.0	130	WO: All DO: All
1.23	0.12	-5.1	10.2	150	WO: All DO: All
1.41	0.04	3.1	6.4	276	WO: All DO: All
1.41	0.13	1.9	10.0	210	WO: All DO: All

1.57	0.03	3.7	6.0	193	WO: All DO: All
1.58	0.13	3.6	9.0	244	WO: All DO: All
1.66	0.08	5.0	17.1	267	WO: All DO: All
1.68	0.10	2.5	7.0	219	WO: All DO: All
1.71	0.13	5.1	10.0	260	WO: All DO: All
1.79	0.10	5.2	5.6	141	WO: All DO: All
1.81	0.07	3.8	9.0	310	WO: All DO: All
1.83	0.12	3.2	12.0	240	WO: All DO: All
2.03	0.03	5.9	8.0	150	WO: All DO: All
2.37	0.24	4.7	3.3	323	WO: All DO: All
0.10	0.00	6.6	7.3	200	WO: LivWRH DO: All
0.12	0.04	5.5	6.1	154	WO: LivWRH DO: All
0.13	0.02	6.3	11.2	202	WO: LivWRH DO: All
0.14	0.05	6.6	10.4	186	WO: LivWRH DO: All
0.14	0.03	6.4	6.4	198	WO: LivWRH DO: All
0.17	0.03	7.5	12.0	190	WO: LivWRH DO: All
0.17	0.01	8.6	2.6	221	WO: LivWRH DO: All
0.18	0.05	5.6	6.0	210	WO: LivWRH DO: All
0.18	0.00	8.1	6.5	192	WO: LivWRH DO: All
0.18	0.06	6.3	11.0	160	WO: LivWRH DO: All
0.18	0.00	12.0	9.0	240	WO: LivWRH DO: All
0.19	0.01	7.2	12.3	178	WO: LivWRH DO: All
0.20	0.01	11.2	9.0	240	WO: LivWRH DO: All
0.20	0.00	7.9	5.2	173	WO: LivWRH DO: All
0.20	0.01	6.4	7.9	210	WO: LivWRH DO: All
0.21	0.02	5.9	11.6	212	WO: LivWRH DO: All
0.22	0.07	7.4	5.0	120	WO: LivWRH DO: All
0.22	0.03	8.6	5.2	107	WO: LivWRH DO: All
0.23	0.01	5.8	5.0	260	WO: LivWRH DO: All
0.25	0.01	4.8			WO: LivWRH DO: All
0.25	0.02	5.5	9.0	170	WO: LivWRH DO: All
0.26	0.14	5.2	14.4	214	WO: LivWRH DO: All

0.26	0.02	6.1	8.6	254	WO: LivWRH DO: All
0.27	0.03	5.7	7.6	194	WO: LivWRH DO: All
0.27	0.03	8.4	10.6	182	WO: LivWRH DO: All
0.27	0.02	5.4	7.0	176	WO: LivWRH DO: All
0.27	0.02	5.2			WO: LivWRH DO: All
0.27	0.05	8.5	11.5	230	WO: LivWRH DO: All
0.27	0.04	8.3	12.7	188	WO: LivWRH DO: All
0.28	0.04	6.3	12.4	210	WO: LivWRH DO: All
0.28	0.02	3.4	12.0	185	WO: LivWRH DO: All
0.29	0.01	3.6	13.0	160	WO: LivWRH DO: All
0.30	0.02	5.9	7.0	204	WO: LivWRH DO: All
0.32	0.01	5.7			WO: LivWRH DO: All
0.32	0.01	8.2	9.9	130	WO: LivWRH DO: All
0.33	0.03	7.8	2.7	346	WO: LivWRH DO: All
0.36	0.02	7.8	3.0	20	WO: LivWRH DO: All
0.38	0.03	9.8	8.5	160	WO: LivWRH DO: All
0.38	0.01	5.4	12.2	249	WO: LivWRH DO: All
0.39	0.03	6.8	5.3	127	WO: LivWRH DO: All
0.39	0.02	6.2	10.0	260	WO: LivWRH DO: All
0.41	0.04	8.0	3.0	20	WO: LivWRH DO: All
0.42	0.01	7.6	2.0	70	WO: LivWRH DO: All
0.45	0.03	6.2	17.0	215	WO: LivWRH DO: All
0.49	0.10	4.1	17.0	210	WO: LivWRH DO: All
0.49	0.04	6.6	8.6	264	WO: LivWRH DO: All
0.50	0.05	5.7	8.1	192	WO: LivWRH DO: All
0.50	0.00	6.2	12.1	253	WO: LivWRH DO: All
0.55	0.14	4.4	9.0	220	WO: LivWRH DO: All
0.64	0.12	6.7	10.0	260	WO: LivWRH DO: All
0.06	0.01	10.3	5.0	300	WO: None DO: All
0.06	0.01	7.6	11.0	240	WO: None DO: All
0.10	0.02	8.2	6.0	226	WO: None DO: All
0.11	0.02	8.0	8.0	170	WO: None DO: All

0.14	0.01	10.4	5.0	293	WO: None DO: All
0.14	0.01	14.1	6.7	342	WO: None DO: All
0.15	0.01	8.5	8.0	179	WO: None DO: All
0.16	0.01	9.3	5.5	300	WO: None DO: All
0.16	0.02	8.6	6.0	217	WO: None DO: All
0.16	0.01	13.5	4.8	346	WO: None DO: All
0.16	0.01	11.1	6.0	300	WO: None DO: All
0.17	0.03	8.6	5.4	199	WO: None DO: All
0.17	0.03	8.6	5.4	190	WO: None DO: All
0.17	0.00	8.5	6.4	200	WO: None DO: All
0.18	0.01	14.2	7.0	130	WO: None DO: All
0.18	0.02	11.6	8.0	290	WO: None DO: All
0.18	0.01	6.2	9.2	254	WO: None DO: All
0.18	0.01	13.3	6.0	170	WO: None DO: All
0.19	0.02	9.0	9.3	170	WO: None DO: All
0.19	0.02	11.5	4.2	303	WO: None DO: All
0.20	0.01	9.6	6.6	144	WO: None DO: All
0.20	0.01	11.3	5.0	260	WO: None DO: All
0.20	0.01	10.7	6.7	280	WO: None DO: All
0.20	0.01	11.4	6.0	100	WO: None DO: All
0.20	0.01	11.4	4.0	270	WO: None DO: All
0.21	0.02	9.9	5.7	305	WO: None DO: All
0.21	0.04	13.1	7.0	330	WO: None DO: All
0.21	0.01	10.9	3.1	77	WO: None DO: All
0.22	0.01	14.4	6.3	344	WO: None DO: All
0.22	0.01	11.6	7.5	210	WO: None DO: All
0.22	0.01	14.0	8.4	118	WO: None DO: All
0.23	0.18	13.5	10.0	80	WO: None DO: All
0.23	0.01	5.9	9.5	230	WO: None DO: All
0.23	0.04	15.4	13.1	261	WO: None DO: All
0.24	0.01	13.4	3.3	324	WO: None DO: All
0.24	0.01	11.3	5.0	230	WO: None DO: All

0.25	0.08	9.6	5.9	151	WO: None DO: All
0.25	0.02	12.4	8.6	293	WO: None DO: All
0.25	0.06	10.1	14.0	220	WO: None DO: All
0.25	0.02	7.5	8.1	211	WO: None DO: All
0.26	0.05	12.4	5.5	337	WO: None DO: All
0.27	0.02	4.3	19.4	200	WO: None DO: All
0.29	0.13	9.0	13.0	310	WO: None DO: All
0.29	0.01	8.0	6.0	227	WO: None DO: All
0.29	0.02	17.1	3.3	321	WO: None DO: All
0.30	0.13	14.7	3.6	341	WO: None DO: All
0.31	0.21	12.7	3.9	182	WO: None DO: All
0.32	0.09	11.1	7.0	30	WO: None DO: All
0.33	0.12	8.9	3.9	301	WO: None DO: All
0.35	0.01	14.6	14.6	282	WO: None DO: All
0.35	0.05	18.7	4.0	290	WO: None DO: All
0.36	0.11	9.7	9.4	146	WO: None DO: All
0.36	0.00	16.1			WO: None DO: All
0.37	0.02	8.4	5.0	190	WO: None DO: All
0.38	0.04	16.8	6.0	320	WO: None DO: All
0.38	0.02	10.8	9.0	140	WO: None DO: All
0.39	0.08	12.5			WO: None DO: All
0.39	0.13	14.1	7.9	60	WO: None DO: All
0.41	0.01	15.4	4.4	96	WO: None DO: All
0.41	0.05	15.7	2.5	16	WO: None DO: All
0.42	0.03	14.6	8.6	87	WO: None DO: All
0.44	0.02	15.2	5.3	61	WO: None DO: All
0.45	0.05	12.0	9.5	135	WO: None DO: All
0.45	0.11	13.5	5.0	179	WO: None DO: All
0.46	0.01	15.3	4.4	101	WO: None DO: All
0.50	0.11	17.9	0.0	0	WO: None DO: All
0.52	0.02	14.4	9.0	90	WO: None DO: All
0.52	0.19	16.1	4.1	280	WO: None DO: All

0.59	0.04	14.4	4.8	50	WO: None DO: All
0.69	0.02	17.1	8.7	93	WO: None DO: All
0.71	0.07	16.1	8.3	73	WO: None DO: All
0.46	0.09	15.9	3.5	180	WO: None DO: None

Table D.3: Results for Flat C at CS2: measured ventilation rates and their uncertainty, temperature difference, wind conditions and the configuration of doors and windows during the measurement time. See Table D.5 for a key of the abbreviations used in describing the door and window configurations.

Ventilation rate (ach)	Combined uncertainty (ach)	T_{in} - T_{out} (ºC)	Wind speed (knots)	Wind direction (º)	Door and window configuration
0.34	0.38	5.3	4.0	210	WO: All DO: All
0.77	0.15	2.2	9.7	314	WO: All DO: All
0.83	0.05	3.1	7.8	220	WO: All DO: All
0.88	0.02	3.2	7.8	240	WO: All DO: All
0.91	0.04	2.5	7.9	266	WO: All DO: All
0.97	0.06	4.6	14.0	250	WO: All DO: All
1.16	0.09	-2.1	6.9	150	WO: All DO: All
1.16	0.05	4.4	14.0	260	WO: All DO: All
1.19	0.06	2.6	9.5	311	WO: All DO: All
1.24	0.03	1.9	6.0	167	WO: All DO: All
1.37	0.05	2.1	5.0	314	WO: All DO: All
1.40	0.03	3.8	12.2	220	WO: All DO: All
1.46	0.07	1.9	5.4	18	WO: All DO: All
1.49	0.02	3.9	7.9	268	WO: All DO: All
1.49	0.06	3.9	5.9	330	WO: All DO: All
1.61	0.14	4.8	12.0	270	WO: All DO: All
1.83	0.12	5.2	7.0	200	WO: All DO: All
1.64	0.05	5.1	11.0	250	WO: All DO: None
0.39	0.05	2.6	10.7	260	WO: BedW DO: All
0.43	0.07	5.3	8.4	218	WO: BedW DO: All
0.63	0.09	8.5	19.0	210	WO: BedW DO: All

0.77	0.02	6.3	7.3	294	WO: BedW DO: All
0.78	0.02	7.0	3.4	196	WO: BedW DO: All
0.99	0.04	6.3	11.8	246	WO: BedW DO: All
1.01	0.02	7.7	5.0	230	WO: BedW DO: All
1.13	0.01	6.0	11.9	208	WO: BedW DO: All
1.18	0.01	8.1	8.8	153	WO: BedW DO: All
1.23	0.02	8.8	15.4	240	WO: BedW DO: All
1.25	0.15	6.4	16.6	224	WO: BedW DO: All
1.33	0.03	8.0	8.2	174	WO: BedW DO: All
1.60	0.04	2.2	12.4	260	WO: BedW DO: All
0.40	0.15	5.1	13.7	234	WO: BedW DO: None
0.46	0.12	5.0	9.0	226	WO: BedW DO: None
0.64	0.03	5.7	8.8	219	WO: BedW DO: None
0.85	0.05	5.9	8.2	240	WO: BedW DO: None
0.96	0.02	6.2	10.3	260	WO: BedW DO: None
1.71	0.10	4.0	16.0	260	WO: BedW DO: None
1.00	0.04	2.1	10.8	209	WO: LivWLHLivWRH DO: All
1.01	0.03	0.5	10.7	214	WO: LivWLHLivWRH DO: All
1.06	0.02	5.7	11.3	244	WO: LivWLHLivWRH DO: All
1.31	0.04	5.1	11.0	160	WO: LivWLHLivWRH DO: All
1.10	0.02	7.1	2.6	280	WO: LivWLHLivWRH DO: None
1.80	0.03	1.9	12.0	220	WO: LivWLHLivWRH DO: None
1.17	0.03	9.6	11.9	260	WO: LivWRH DO: None
1.28	0.05	7.7	14.7	237	WO: LivWRHBedW DO: All
1.74	0.09	7.0	6.8	299	WO: LivWRHBedW DO: All
0.08	0.09	11.0	11.0	110	WO: None DO: All
0.09	0.01	10.5	7.0	270	WO: None DO: All
0.14	0.08	7.5	8.0	170	WO: None DO: All
0.14	0.05	11.1	14.0	210	WO: None DO: All
0.15	0.03	10.4	13.5	206	WO: None DO: All
0.16	0.03	10.8	2.0	270	WO: None DO: All
0.17	0.03	9.1	10.3	177	WO: None DO: All

0.20	0.03	8.8	13.4	198	WO: None DO: All
0.21	0.02	10.3	5.9	216	WO: None DO: All
0.21	0.02	8.5	5.0	160	WO: None DO: All
0.21	0.03	11.7	8.4	180	WO: None DO: All
0.22	0.02	9.0	11.0	173	WO: None DO: All
0.22	0.04	10.5	7.3	200	WO: None DO: All
0.23	0.01	9.1	9.1	139	WO: None DO: All
0.23	0.01	8.9	9.4	140	WO: None DO: All
0.26	0.04	9.2	6.0	170	WO: None DO: All
0.27	0.01	8.1	18.1	246	WO: None DO: All
0.28	0.06	13.5	5.0	186	WO: None DO: All
0.30	0.02	10.7	3.0	199	WO: None DO: All
0.30	0.04	12.0	4.6	50	WO: None DO: All
0.30	0.01	9.6	12.0	230	WO: None DO: All
0.31	0.02	8.5	10.0	130	WO: None DO: All
0.32	0.01	12.5	5.7	257	WO: None DO: All
0.34	0.02	11.7	12.9	207	WO: None DO: All
0.35	0.01	10.8	6.0	293	WO: None DO: All
0.35	0.03	7.3	11.0	220	WO: None DO: All
0.36	0.05	7.7	2.3	343	WO: None DO: All
0.38	0.02	11.4	11.9	95	WO: None DO: All
0.40	0.02	8.1	8.4	60	WO: None DO: All
0.40	0.02	8.7	7.6	60	WO: None DO: All
0.43	0.04	4.0	7.0	270	WO: None DO: All
0.43	0.01	8.0	5.9	73	WO: None DO: All
0.45	0.02	7.9	10.5	141	WO: None DO: All
0.45	0.04	9.6	7.7	82	WO: None DO: All
0.45	0.02	9.3	6.3	53	WO: None DO: All
0.47	0.08	8.1	3.3	322	WO: None DO: All
0.48	0.02	8.4	20.6	244	WO: None DO: All
0.48	0.02	13.6	3.8	79	WO: None DO: All
0.50	0.02	11.4	5.0	260	WO: None DO: All

0.52	0.01	13.2	4.0	203	WO: None DO: All
0.53	0.02	13.0	2.5	207	WO: None DO: All
0.53	0.02	10.1	7.6	307	WO: None DO: All
0.55	0.04	7.3	2.4	11	WO: None DO: All
0.56	0.03	11.8	4.0	280	WO: None DO: All
0.57	0.07	9.4	9.0	320	WO: None DO: All
0.57	0.02	6.9	4.5	31	WO: None DO: All
0.58	0.02	12.3	9.0	21	WO: None DO: All
0.59	0.04	8.9	9.5	240	WO: None DO: All
0.60	0.02	13.2	8.6	30	WO: None DO: All
0.61	0.01	8.7	11.3	244	WO: None DO: All
0.65	0.02	12.0	8.7	91	WO: None DO: All
0.65	0.02	10.2	10.0	220	WO: None DO: All
0.71	0.03	13.3	8.9	35	WO: None DO: All
0.71	0.02	13.8	10.4	40	WO: None DO: All
0.76	0.12	6.2	18.2	218	WO: None DO: All
0.83	0.12	5.7	13.5	295	WO: None DO: All
0.85	0.03	9.7	9.0	302	WO: None DO: All
0.85	0.03	12.8	9.0	36	WO: None DO: All
1.03	0.04	6.3	15.6	220	WO: None DO: All
1.07	0.06	11.0	10.8	249	WO: None DO: All
0.10	0.02	11.1	6.3	333	WO: None DO: None
0.10	0.01	10.8	9.0	200	WO: None DO: None
0.11	0.03	12.0	11.1	265	WO: None DO: None
0.15	0.05	10.9	5.0	243	WO: None DO: None
0.16	0.05	11.0	6.0	260	WO: None DO: None
0.16	0.03	9.7	7.5	285	WO: None DO: None
0.16	0.10	8.1	9.4	257	WO: None DO: None
0.18	0.05	9.5	4.0	344	WO: None DO: None
0.20	0.05	10.7	14.0	280	WO: None DO: None
0.20	0.13	9.7	7.0	110	WO: None DO: None
0.21	0.04	7.5	5.6	257	WO: None DO: None

0.21	0.02	8.2	10.0	260	WO: None DO: None
0.22	0.06	12.7	7.0	260	WO: None DO: None
0.23	0.03	12.4	14.0	260	WO: None DO: None
0.24	0.06	10.0	8.0	290	WO: None DO: None
0.25	0.08	9.4	6.1	40	WO: None DO: None
0.25	0.04	10.4	1.2	4	WO: None DO: None
0.26	0.04	10.6	13.6	274	WO: None DO: None
0.26	0.07	11.3	7.0	334	WO: None DO: None
0.27	0.11	10.7	7.0	40	WO: None DO: None
0.27	0.06	10.6	7.6	10	WO: None DO: None
0.27	0.06	12.1	10.0	210	WO: None DO: None
0.28	0.08	10.9	8.0	80	WO: None DO: None
0.28	0.07	7.3	5.0	237	WO: None DO: None
0.30	0.03	12.2	4.0	330	WO: None DO: None
0.30	0.11	10.0	15.3	235	WO: None DO: None
0.31	0.01	11.4	13.0	197	WO: None DO: None
0.32	0.03	12.0	16.0	200	WO: None DO: None
0.32	0.02	10.2	8.0	296	WO: None DO: None
0.32	0.01	10.7	2.3	343	WO: None DO: None
0.32	0.01	6.2	5.4	265	WO: None DO: None
0.33	0.01	12.1	12.0	190	WO: None DO: None
0.33	0.05	11.6	11.4	215	WO: None DO: None
0.34	0.03	11.5	6.6	343	WO: None DO: None
0.35	0.01	10.8	9.6	197	WO: None DO: None
0.35	0.02	10.7	10.0	271	WO: None DO: None
0.35	0.01	11.5	10.6	10	WO: None DO: None
0.36	0.16	8.8	10.1	269	WO: None DO: None
0.37	0.01	11.6	12.7	130	WO: None DO: None
0.39	0.09	10.1	15.5	184	WO: None DO: None
0.40	0.03	12.9	3.0	360	WO: None DO: None
0.40	0.05	9.8	12.0	260	WO: None DO: None
0.40	0.02	12.8	6.0	295	WO: None DO: None

0.41	0.02	13.4	7.0	106	WO: None DO: None
0.43	0.04	8.6	14.2	218	WO: None DO: None
0.45	0.04	12.1	10.0	200	WO: None DO: None
0.45	0.04	13.1	4.3	276	WO: None DO: None
0.45	0.05	12.0	6.4	130	WO: None DO: None
0.45	0.02	10.5	14.0	210	WO: None DO: None
0.46	0.04	11.9	10.0	201	WO: None DO: None
0.47	0.07	10.6	8.8	88	WO: None DO: None
0.47	0.13	10.7	8.0	80	WO: None DO: None
0.47	0.02	13.1	4.3	114	WO: None DO: None
0.49	0.02	12.9	11.0	5	WO: None DO: None
0.49	0.01	13.3	8.2	220	WO: None DO: None
0.49	0.01	9.2	12.0	106	WO: None DO: None
0.51	0.01	12.3	13.6	280	WO: None DO: None
0.51	0.04	13.3	4.7	105	WO: None DO: None
0.52	0.01	12.0	10.5	4	WO: None DO: None
0.52	0.01	13.2	2.1	35	WO: None DO: None
0.52	0.04	9.8	11.1	119	WO: None DO: None
0.53	0.04	7.0	18.0	170	WO: None DO: None
0.53	0.02	11.6	3.0	324	WO: None DO: None
0.55	0.02	11.4	5.8	110	WO: None DO: None
0.56	0.07	10.6	14.7	260	WO: None DO: None
0.57	0.02	9.4	11.9	254	WO: None DO: None
0.58	0.06	9.0	11.0	100	WO: None DO: None
0.58	0.03	10.5	15.2	310	WO: None DO: None
0.59	0.02	12.4	9.7	84	WO: None DO: None
0.62	0.01	14.1	9.9	10	WO: None DO: None
0.63	0.04	11.1	15.4	310	WO: None DO: None
0.64	0.02	5.5	5.1	270	WO: None DO: None
0.64	0.03	10.2	17.0	270	WO: None DO: None
0.64	0.07	12.2	5.4	315	WO: None DO: None
0.64	0.10	9.0	8.3	270	WO: None DO: None

0.70	0.02	11.7	8.3	22	WO: None DO: None
0.72	0.09	11.1	13.4	260	WO: None DO: None
0.76	0.04	7.7	17.0	246	WO: None DO: None
0.79	0.01	12.1	3.9	313	WO: None DO: None
0.80	0.03	11.8	15.0	284	WO: None DO: None
0.80	0.03	8.5	15.4	226	WO: None DO: None
0.81	0.02	10.2	16.7	180	WO: None DO: None
0.85	0.02	9.6	14.5	240	WO: None DO: None
0.86	0.04	8.9	14.6	211	WO: None DO: None
0.87	0.02	8.4	13.0	240	WO: None DO: None
1.18	0.02	5.1	6.5	293	WO: None DO: None
1.18	0.01	13.0			WO: None DO: None
1.29	0.07	9.3	15.0	220	WO: None DO: None

Table D.4: Results for Flat D at CS2: measured ventilation rates and their uncertainty, temperature difference, wind conditions and the configuration of doors and windows during the measurement time. See Table D.5 for a key of the abbreviations used in describing the door and window configurations.

Ventilation rate (ach)	Combined uncertainty (ach)	T_{in} - T_{out} (°C)	Wind speed (knots)	Wind direction (°)	Door and window configuration
0.10	0.04	5.5	7.0	210	WO: None DO: All
0.13	0.01	6.1	8.7	204	WO: None DO: All
0.13	0.07	2.4	10.0	260	WO: None DO: All
0.13	0.04	4.5			WO: None DO: All
0.13	0.08	0.9	10.0	170	WO: None DO: All
0.16	0.09	1.4	12.6	210	WO: None DO: All
0.17	0.02	6.1	9.0	181	WO: None DO: All
0.18	0.03	6.1	9.0	190	WO: None DO: All
0.19	0.03	4.8	12.1	245	WO: None DO: All
0.19	0.06	4.6	7.0	178	WO: None DO: All
0.20	0.01	6.2	11.0	256	WO: None DO: All
0.21	0.04	3.9	14.2	233	WO: None DO: All

0.22	0.08	2.1	14.2	246	WO: None DO: All
0.22	0.03	3.8	8.0	26	WO: None DO: All
0.22	0.04	4.3	11.7	259	WO: None DO: All
0.24	0.02	7.8	14.8	240	WO: None DO: All
0.25	0.02	7.5	4.3	205	WO: None DO: All
0.25	0.01	5.2	11.5	210	WO: None DO: All
0.25	0.07	11.9	14.3	235	WO: None DO: All
0.25	0.07	8.3	5.0	294	WO: None DO: All
0.26	0.19	0.4	10.0	220	WO: None DO: All
0.26	0.02	5.5	14.0	240	WO: None DO: All
0.26	0.04	6.9	17.4	266	WO: None DO: All
0.26	0.03	0.5	11.4	220	WO: None DO: All
0.26	0.02	5.4	8.6	206	WO: None DO: All
0.27	0.04	4.5	11.1	260	WO: None DO: All
0.27	0.05	6.3	14.5	254	WO: None DO: All
0.28	0.03	6.6	14.0	240	WO: None DO: All
0.30	0.06	2.6	11.8	240	WO: None DO: All
0.30	0.05	3.4	15.0	250	WO: None DO: All
0.30	0.02	0.8	8.6	233	WO: None DO: All
0.30	0.01	4.6			WO: None DO: All
0.30	0.02	5.0	12.0	238	WO: None DO: All
0.31	0.10	2.3	10.0	200	WO: None DO: All
0.31	0.05	4.9	10.0	260	WO: None DO: All
0.31	0.03	5.1	11.0	160	WO: None DO: All
0.32	0.05	9.6	8.0	290	WO: None DO: All
0.32	0.10	5.1	10.0	260	WO: None DO: All
0.32	0.05	4.3	17.9	219	WO: None DO: All
0.32	0.03	5.5	7.0	253	WO: None DO: All
0.32	0.06	2.1	14.0	240	WO: None DO: All
0.32	0.03	4.1	7.8	15	WO: None DO: All
0.33	0.03	8.0	15.2	251	WO: None DO: All
0.33	0.03	5.1	16.7	230	WO: None DO: All

0.33	0.06	4.9	15.0	250	WO: None DO: All
0.33	0.06	-3.8	10.0	173	WO: None DO: All
0.33	0.08	4.6	8.5	267	WO: None DO: All
0.33	0.05	4.9	6.7	257	WO: None DO: All
0.34	0.01	4.4	16.3	239	WO: None DO: All
0.34	0.15	1.2	13.0	210	WO: None DO: All
0.34	0.07	5.2	13.8	234	WO: None DO: All
0.34	0.01	4.2			WO: None DO: All
0.34	0.01	7.2	6.8	200	WO: None DO: All
0.34	0.04	8.4	9.9	141	WO: None DO: All
0.34	0.02	5.3	8.2	178	WO: None DO: All
0.35	0.02	7.5	18.6	250	WO: None DO: All
0.35	0.02	4.7			WO: None DO: All
0.35	0.04	3.9			WO: None DO: All
0.35	0.02	-4.8	10.9	203	WO: None DO: All
0.35	0.10	0.6	13.3	215	WO: None DO: All
0.35	0.04	5.6	14.0	231	WO: None DO: All
0.35	0.08	1.9	14.0	250	WO: None DO: All
0.35	0.03	5.2	14.0	200	WO: None DO: All
0.36	0.01	4.9	13.2	248	WO: None DO: All
0.36	0.08	2.9	12.0	200	WO: None DO: All
0.36	0.03	4.8	7.4	175	WO: None DO: All
0.37	0.01	6.0	11.3	264	WO: None DO: All
0.38	0.01	-2.3	9.5	216	WO: None DO: All
0.38	0.03	5.4			WO: None DO: All
0.38	0.03	2.5	14.0	232	WO: None DO: All
0.38	0.02	0.1	7.0	194	WO: None DO: All
0.38	0.04	10.3	8.0	291	WO: None DO: All
0.38	0.08	4.8	5.0	130	WO: None DO: All
0.38	0.05	13.3	13.9	257	WO: None DO: All
0.38	0.01	6.5	6.0	224	WO: None DO: All
0.39	0.01	5.1	6.0	190	WO: None DO: All

0.39	0.03	4.8	6.2	162	WO: None DO: All
0.40	0.03	0.2	9.4	180	WO: None DO: All
0.40	0.02	6.2	9.4	212	WO: None DO: All
0.40	0.04	-8.3	11.0	159	WO: None DO: All
0.40	0.03	0.9	9.6	190	WO: None DO: All
0.40	0.12	-2.9	10.0	110	WO: None DO: All
0.40	0.06	4.6	17.0	254	WO: None DO: All
0.41	0.10	3.1	12.6	206	WO: None DO: All
0.41	0.01	3.8	11.8	211	WO: None DO: All
0.41	0.05	7.2	9.0	185	WO: None DO: All
0.41	0.03	3.8	10.4	224	WO: None DO: All
0.41	0.07	-0.9	9.5	175	WO: None DO: All
0.41	0.10	1.2	5.0	149	WO: None DO: All
0.41	0.07	3.7	11.2	194	WO: None DO: All
0.42	0.18	2.5	18.0	210	WO: None DO: All
0.42	0.08	4.2	7.0	170	WO: None DO: All
0.42	0.16	10.4	11.0	120	WO: None DO: All
0.42	0.02	1.9	8.1	239	WO: None DO: All
0.42	0.06	3.4	7.0	270	WO: None DO: All
0.42	0.02	7.7	9.8	202	WO: None DO: All
0.43	0.04	4.3	17.2	210	WO: None DO: All
0.43	0.02	4.6	6.0	210	WO: None DO: All
0.44	0.01	4.8	8.2	212	WO: None DO: All
0.44	0.07	3.6	13.0	206	WO: None DO: All
0.44	0.02	6.3	14.1	240	WO: None DO: All
0.45	0.03	8.0	9.0	199	WO: None DO: All
0.45	0.01	4.2	8.8	229	WO: None DO: All
0.46	0.03	4.7	11.0	169	WO: None DO: All
0.46	0.03	4.0	15.9	240	WO: None DO: All
0.46	0.02	3.0	8.0	249	WO: None DO: All
0.46	0.01	3.4	13.9	245	WO: None DO: All
0.47	0.07	3.4	13.7	240	WO: None DO: All

0.47	0.03	-6.3	10.5	150	WO: None DO: All
0.47	0.01	5.2	14.7	243	WO: None DO: All
0.47	0.03	3.7	9.5	241	WO: None DO: All
0.47	0.02	5.2	14.3	211	WO: None DO: All
0.48	0.02	4.7	12.0	240	WO: None DO: All
0.49	0.12	3.2	11.0	190	WO: None DO: All
0.49	0.01	6.8	11.6	246	WO: None DO: All
0.50	0.06	5.3	12.0	251	WO: None DO: All
0.50	0.04	5.8	9.9	250	WO: None DO: All
0.50	0.01	7.3	6.0	244	WO: None DO: All
0.50	0.01	4.3	9.2	220	WO: None DO: All
0.50	0.02	5.5	11.5	206	WO: None DO: All
0.51	0.04	6.4	12.0	180	WO: None DO: All
0.51	0.03	4.9	12.0	260	WO: None DO: All
0.51	0.10	6.3	10.3	302	WO: None DO: All
0.52	0.02	8.1	9.0	240	WO: None DO: All
0.53	0.02	2.1	8.6	217	WO: None DO: All
0.53	0.03	10.2			WO: None DO: All
0.53	0.04	6.1	13.7	255	WO: None DO: All
0.53	0.01	4.8	12.4	244	WO: None DO: All
0.54	0.02	4.6	14.0	260	WO: None DO: All
0.54	0.03	7.9	10.3	77	WO: None DO: All
0.54	0.03	4.4	17.0	210	WO: None DO: All
0.54	0.01	6.8	14.9	241	WO: None DO: All
0.54	0.02	6.8	15.6	240	WO: None DO: All
0.55	0.19	-3.9	11.0	220	WO: None DO: All
0.55	0.04	6.1	10.0	164	WO: None DO: All
0.56	0.13	6.3	13.6	194	WO: None DO: All
0.56	0.02	4.6	14.0	260	WO: None DO: All
0.57	0.02	4.1	11.9	242	WO: None DO: All
0.57	0.02	4.9	4.2	160	WO: None DO: All
0.57	0.02	5.4	8.3	170	WO: None DO: All

0.58	0.07	5.3	10.5	285	WO: None DO: All
0.59	0.04	6.6	5.7	162	WO: None DO: All
0.59	0.04	6.4	5.4	160	WO: None DO: All
0.61	0.04	5.5	17.7	220	WO: None DO: All
0.61	0.02	5.5	14.1	220	WO: None DO: All
0.61	0.10	4.0	5.0	250	WO: None DO: All
0.62	0.02	5.3	10.0	260	WO: None DO: All
0.62	0.02	7.1	8.6	157	WO: None DO: All
0.63	0.02	6.5	7.0	340	WO: None DO: All
0.64	0.11	4.0	8.7	223	WO: None DO: All
0.64	0.03	5.5	11.5	210	WO: None DO: All
0.65	0.03	4.7	6.0	224	WO: None DO: All
0.67	0.02	4.3	7.9	10	WO: None DO: All
0.67	0.01	3.0	7.6	211	WO: None DO: All
0.67	0.05	5.2	18.9	211	WO: None DO: All
0.68	0.02	4.4	9.0	228	WO: None DO: All
0.69	0.03	7.3	8.4	178	WO: None DO: All
0.69	0.01	6.2	11.4	185	WO: None DO: All
0.71	0.03	4.9	17.0	219	WO: None DO: All
0.72	0.05	9.0	9.0	240	WO: None DO: All
0.74	0.03	6.3	11.8	183	WO: None DO: All
0.75	0.09	1.2	8.0	80	WO: None DO: All
0.77	0.01	6.1	8.0	358	WO: None DO: All
0.77	0.02	7.5	10.0	210	WO: None DO: All
0.78	0.02	4.3	5.9	110	WO: None DO: All
0.81	0.08	12.5	3.3	351	WO: None DO: All
0.87	0.03	9.7	9.0	90	WO: None DO: All
0.93	0.02	9.7	8.4	84	WO: None DO: All
1.07	0.04	7.3	5.0	90	WO: None DO: All

Table D.5: Key for the abbreviations used in Tables D.1 to D.4 to describe the configurations of doors and windows during measurement times.

Abbreviation	Explanation
W	Window
D	Door
O	Open
Bed	Bedroom
Bath	Bathroom
Liv	Living room
LH	Left hand
RH	Right hand
M	Middle