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Occupant window opening behaviour: the relative importance of temperature and carbon dioxide in university office buildings

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Declaration

All work presented within this thesis is my own work, except when specific reference has been made to the work of others

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Summary

Occupant window opening behaviour has become of increasing concern because of the role windows play in controlling ventilation and hence in building energy consumption. Previous studies (in different countries, climates, buildings and room types and over different observation periods) have shown a general trend that window opening is related to weather conditions, indoor temperature and some non-environmental conditions. However, seeking to reduce the amount of energy lost through ventilation and infiltration can be conflicting with the need to maintain high indoor air quality (IAQ) levels. Carbon dioxide (CO_2) which is an occupant generated pollutant and also a good indicator of ventilation and IAQ is known to have negative physiological impacts on occupants. It is therefore important to seek to understand occupants' interaction with building controls in response to changes in IAQ as well as changes in thermal conditions.

The work described in this thesis is focussed on window opening behaviour of occupants in university buildings. The influence of indoor and outdoor environmental variables on window opening will be assessed. Also the influence of CO_2, as an indicator of IAQ, on window opening will be considered. Field observations were conducted in two naturally ventilated office buildings over three different seasons. Window states, window state changing events and environmental data were measured during the survey periods. An experiment with controlled conditions was also conducted to investigate the influence of CO_2 concentration in different thermal conditions. This was achieved by observing participants window use in environments with pre-set CO_2 and temperature conditions.

Results from these studies confirmed that window opening behaviour is heavily influenced by temperature. However, temperature alone did not explain all the variance in the observed behaviour. Differences were found in behaviour at different times of the day and in different seasons as different combinations of variables affected window opening at different times. From the experiment, it was found that perceived environment was also significantly associated with window opening.

Based on the observations made in this study, models for window opening were generated for both indoor and outdoor temperature. These were compared with models from previous studies and it was shown that there is a range in the prediction of window opening. The comparison highlighted the disparities between the window opening models and questions the generalizability and reliability of the models, highlighting the need to consider the effects of a wider range of variables.

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1.1 Background

Common or most likely responses to the question as to why windows are opened may be to feel cooler, for fresh air and/or to get rid of odours. In homes, and particularly in rooms like bathrooms, it may also be to reduce humidity and thus reduce the risk of condensation. Occupants may open windows because it is part of their routine or it is a habit. The impacts of window opening extend to the performance of buildings. With a move towards reducing building energy consumption and improving indoor environments, understanding the role of occupants in controlling their indoor environment demands increasing attention as it is important to design and predict the performance of buildings.

Window opening provides a dual role in regulating indoor temperatures and diluting indoor air pollutants through increasing air flow and air change rate. Indoor temperature, humidity and indoor air quality are elements of the indoor environment which have effects on occupant comfort, health and work performance and productivity. Earlier studies have shown an effect of temperature, humidity, ventilation rates and indoor air quality on occupant health and work performance (Bakó-Biró, Kochhar, Clements-Croome, Awbi, & Williams, 2007; Bakó-Biró, Clements-Croome, Kochhar, Awbi, & Williams, 2012; Daisey, Angell, & Apte, 2003; Fang, Wyon, Clausen, & Fanger, 2004; Wargocki, Wyon, & Sundell, 2000). These observations have been made in occupants at home (Bornehag *et al.* 2005; Lindfors *et al.* 1995; Williamson *et al.* 1997), in schools (Haverinen-Shaughnessy *et al.* 2011; Coley & Greeves 2004) and in offices (Wargocki *et al.* 1999; Seppänen *et al.* 2006). In offices, poor indoor air quality can have an economic impact on businesses as earlier studies have found that the economic benefits of increasing minimum ventilation rate far exceed the energy-related benefits (Fisk *et al.* 2011).

In heated spaces window opening can have an energy implication as the rate of heat loss is increased when a window is opened. Hence, to realise the potential of reducing building energy use it makes sense to increase building airtightness in order to reduce infiltration. If infiltration provides significant additional dilution of indoor air pollutants, measures to improve airtightness will lead to greater dependency on appropriate ventilation design to maintain adequate indoor air quality. Therefore, developing a greater understanding of window use becomes imperative to understand the quality of our indoor environment. In naturally ventilated buildings, windows have been found to be the most widely used adaptive action to control temperature (Nicol 2001; Haldi & Robinson 2008). Earlier observations of window opening were made in studies that were focussed on investigating air change rate and its implication on building energy consumption (Dick & Thomas 1951; Brundrett 1977; Dubrul 1988). Since then several studies have been conducted to investigate the factors that drive window opening and to improve the prediction of occupant behaviour for building simulation.

In the studies conducted by Dick & Thomas (1951) and Brundrett (1977) window states were manually recorded in direct observations by researchers or by the occupants themselves (self reporting). These studies found that outdoor temperature was significantly associated with the proportion of windows open. Later studies aimed at investigating the factors that influence window opening used direct observation (Nicol 2001; Haldi & Robinson 2008; Zhang & Barrett 2012) and indoor surveys (Fritsch & Kohler 1990; Yun & Steemers 2008; Herkel *et al.* 2008; Haldi & Robinson 2009). In indoor surveys, data loggers are used to continuously record environmental conditions and window use (changing states) and this allows indoor parameters as well as outdoor parameters to be included in the analysis of factors that may influence window opening behaviour. These studies have confirmed that outdoor temperature drives window opening and have also shown that indoor temperature is an equally significant predictor of window opening. Another observation that has been reported is the time of day variation in occupant window use behaviour (Yun & Steemers 2008; Haldi & Robinson 2009). In offices, where the work day is split into three periods (arrival, occupancy or intermittent and departure), window opening occurs mainly on arrival and window closing occurs mainly at departure. During the intermittent period between arrival and departure, only a small proportion of state change events occur.

Probabilistic models of window opening behaviour have been generated from these earlier observations (Herkel *et al.* 2008; Rijal *et al.* 2007; Haldi & Robinson 2009). Probabilistic models describe data observed from a system. In window opening studies, this system is the observed window state and the variables, usually environmental variables, which are recorded. The probability of a window state is inferred by the measured environmental variables. Comparison of the probabilistic models generated from the earlier studies showed that the relations between the predictors and window open are generally similar. For example, the probability of windows open increases with increasing outdoor temperature or increasing indoor temperature. However, there is always a variation in the calculated probabilities from different models at any given value of the predictor. This variation may be due to the method used in the collecting data, the location of the building or the type of building observed. However, the variation indicates that window opening is not only governed by the single predictor investigated but by other factors as well. These other factors could be occupant related, building related or environment related. It is therefore important to investigate a range of factors that can have an impact on occupant behaviour and not just a single variable.

One environmental parameter that is of interest is indoor concentration of carbon dioxide (CO_2). CO_2 is an indoor air pollutant which increases dependent on the number of occupants in a room. Because it is mainly produced by occupants, the resultant increase in indoor CO_2 concentration above outdoor levels is used to deduce ventilation efficiency. CO_2 concentration has known physiological effects on occupants. Earlier studies have shown the impact of increasing CO_2 concentration on occupant comfort, health and work performance (e.g. Apte *et al.* 2000; Shendell *et al.* 2004; Stenberg *et al.* 1994). This has been found in both field observations (e.g. Seppänen *et al.* 1999) and experiments conducted in climate chambers (e.g. Kajtar *et al.* 2003). In a review of epidemiological studies carried out in offices to assess the association of CO_2 on sick building syndrome (SBS) symptoms and perceived air quality, statistically significant associations were found between elevated CO_2 concentration and the prevalence of SBS symptoms (Seppänen *et al.* 1999). In schools, a significant association has also been found between increasing CO_2 concentrations and increasing health symptoms and decreasing concentration on work (Myhrvold *et al.* 1996). In homes, increase in CO_2 concentration has been linked with an increase in asthmatic symptoms (Norbäck *et al.* 1995). Even at what would be considered a medium/moderate indoor air quality rating (resulting in CO_2 concentrations of 1200ppm) it has been suggested that up to 50% of the population of occupants will demonstrate SBS symptoms (Carpenter & Poitrast 1990). Sick building syndrome symptoms have also been found to occur at CO_2 levels increasing from 800ppm (Tsai *et al.* 2012).

The earlier studies on window opening mentioned above have shown a link between temperature and use of windows. This provides useful understanding into what drives the majority of window use. However, what about at lower temperatures, will occupants be likely to open the window due to other factors (e.g. rising CO_2 concentration)? Previously, this has not been possible to investigate due to a lack of monitored variables and also the overriding impact of temperature in the field studies. Investigating the effects of occupant control on ventilation and IAQ and ultimately on building energy performance is necessary to better predict building performance. Better prediction leads to better design – design of buildings which also achieve and maintain adequate indoor air quality for occupant comfort, health and work performance and productivity.

1.2 Aims and objectives

The variations in the window opening models which are based on indoor and outdoor temperatures suggest that factors other than thermal conditions need to be taken into account when investigating window opening behaviour. The aim of this project was to investigate the factors that influence window opening and to extend the understanding of occupant window opening behaviour.

The specific objectives for the study were to:

1. Identify the environmental factors that are correlated with window open state.
2. Compare window opening predictions determined by using different field survey methods.
3. Identify the environmental factors that influence window opening in different periods of the day and in different seasons and develop appropriate predictive models for window opening.
4. Compare the relative importance of temperature and CO_2 concentration on window opening.

1.3 Layout of thesis

Chapter 1 has presented a context for this study which is the importance of adequate indoor air quality for occupancy and role of window opening as an adaptive control. In order to further understand the importance of the current project, Chapter 2 presents a detailed literature review which analyses past work on environmental criteria and window opening behaviour. It presents the recommended standards of indoor environments and the known impacts of ventilation and indoor air quality on occupants. Focus is given to indoor CO_2 concentration and its impact on occupant comfort, health and productivity. An extensive review of studies conducted to investigate occupant window opening behaviour and the resulting models generated is presented by describing the methods used and the results obtained.

In order to assess the variation in the predictive models due to survey method (objective 2), two different field surveys were conducted to investigate the factors that are correlated with window open state which are presented in Chapters 3 to 5. Chapter 3 contains detailed descriptions of the selected buildings and instrumentation used in the field survey and in the experiment. In chapter 4, the photographic survey method and results are presented. This survey type is used in order to observe a large proportion of windows and investigate the external environmental factors that predict window state (objective 1). In chapter 5, details of the indoor survey and the results are presented. In the indoor survey CO_2 concentration was measured and included in the analysis as a possible predictor of window opening (objective 3).

To further investigate the role of CO_2 concentration as a significant predictor of window opening, an experiment with controlled conditions was conducted. The aim was to assess the relative importance of CO_2 on window opening in thermally comfortable environments. Chapter 6 relates to Objective 4 where the experiment methodology (environmental conditions, sample size, experiment duration and procedure) and the results are presented.

Chapter 7 draws together the results from the three methods, discussing the similarities and the differences in the results from the field surveys to discuss the variation in the resulting predictive models. Finally, the significance of different variables on windows open due to different time periods and seasonal changes is analysed.

Chapter 8 provides the conclusion, summarising the findings of the current study. Suggestions for further work are also presented at the end of this chapter.

2 Literature review

2.1 Energy use in buildings

2.2 Recommended standards for indoor environments

2.3 Occupant window opening behaviour

2.4 Summary

2.1 Energy use in buildings

Human beings spend approximately 80% to 90% of their time indoors (BRE 2014). Buildings offer a place primarily for shelter and security from the outside where conditions can be harsh and harmful. Because of the amount of time spent indoors, buildings are also required to be comfortable and healthy for their occupants. In order to achieve this, energy is often expended for operations such as heating, cooling and lighting. In the UK, buildings account for approximately 42% of the total primary energy supplied and they account for approximately 43% of total emissions (18% from domestic buildings and 25% from non-domestic buildings) (DECC 2013). In Europe these figures are 40% of total primary energy supplied and 36% for total carbon emission and in the United States they are 41% of total primary energy and 40% of the nation’s total emissions (U.S. Department of Energy 2011). The majority of the energy consumed during the operation of the buildings is for thermal comfort (space heating and cooling), however, building energy use by end-user is also generally dependent on a number of factors, e.g. climate and type of building (GEA 2012). In commercial offices, over half of the total energy consumed is used for space heating and in the UK, this proportion is approximately 53% (DECC 2013).

Increase in the understanding of global warming, its effect on the environment, economy and health and the increasing evidence of the limited source of major energy supply are having a significant impact on decisions made in areas including the design, construction and use of buildings (IPCC 2007; Stern 2006). This is a global issue and so countries around the world are taking measures to enable a reduction in carbon emissions to be met (CCC 2008; European Commission 2014; U.S. Department of State 2014).

Because of the significant amount of energy used and emissions produced from buildings, the building sector represents a substantial energy saving and emissions reduction potential. Particularly, in the UK, reducing the amount of energy used in space heating will be instrumental in efforts to reduce energy consumption. This can be achieved through interventions such as improved insulation and air tightness of the building envelope. Improving airtightness will have important implications for ventilation in buildings. As the air change rate affects both building energy consumption and the indoor environment, in buildings where occupants have control over the ventilation and the indoor environment, their actions also affect the energy performance of the building. Understanding occupant behaviour or control over these elements is therefore vital in the design of energy efficient buildings.

2.1.1 Towards energy efficiency in UK buildings

Modifications in building design, construction and operation, to some extent, are being driven by the need for increased energy efficiency with the aim to reduce energy use and emissions from the buildings. In the UK, building regulations and standards are being revised and improved to ensure reduction in energy use and emissions. Other tangible benefits from the proposed energy efficiency measures include improvement in design and operation of buildings and the provision of better working environments, in terms of the comfort and health needs of occupants (CIBSE 2004).

As part of the objectives to reduce energy consumption and emissions, the EU initiatives include targets to increase energy efficiency by 20% by 2020 in buildings (European Commission 2014). The UK government has also published plans for all new dwellings and new non-domestic buildings to be zero carbon by 2016 and 2019 respectively (UKGBC 2014). These will be achieved through the application of revised building regulations (Part L) and standards which set specifications for building fabric energy efficiency and energy efficient services. Changes made to regulations such as Part L present improvements in building fabric and energy performance. The main requirement of Part L of the Building Regulations is for reasonable provision to be made for the conservation of fuel and power by limiting the heat loss through the fabric of the building.

Heat loss from buildings can be due to ventilation, both controlled and uncontrolled or through the building fabric. Uncontrolled ventilation is also known as infiltration and it occurs through cracks in the building envelope (e.g. around poorly fitted windows and doors). Controlled ventilation is usually by means of natural, mixed-mode or mechanical ventilation systems. Fabric heat loss is thermal conduction through the fabric elements (wall, windows, floor and roof). Improvement in construction standards (sealing cracks and draught proofing windows and doors) ensure that buildings are more airtight. Heat loss through the building fabric is also tackled with decreasing U-values of building elements.

In the revised Part L of the Building Regulations, U-values have been reduced and also made more detailed. A U-value is a measure of heat loss in building elements (walls, roof, windows and floor) or how well heat is transmitted through the building elements. It is expressed in $W/m^2 K$ so that for a one degree difference in temperature either side of the building element, one watt of heat energy will be transmitted through one square metre of the building element. This indicates that the lower the U-value the better the thermal performance of the building element (i.e. less heat is transmitted at each temperature difference). These are central to energy efficiency in buildings as they reduce the amount of unnecessary heat loss from the building fabric. The level of airtightness achieved in a building is measured as air permeability. Air permeability is also specified by the Building Regulations ($10m^3/m^2/hr$ @ 50Pa or lower for non-domestic buildings). Lower air permeability values indicate increased airtightness. In the recent revision of Part L, for all new non-domestic buildings, a 9% reduction in emissions is required compared to the 2010 standard and all buildings with a gross internal floor area of $500m^2$ and over are required to be tested for airtightness compliance (Building Regulation 2013). These buildings have to achieve the specified $10m^3/m^2/hr$ or lower.

2.1.2 Concerns associated with energy efficiency measures

For domestic buildings, one feature of the definition of zero carbon homes is that they have to be desirable and healthy homes (CLG 2008).The UK government considers that it would not be acceptable if zero carbon homes were less desirable or less healthy than those under current standards. In commercial buildings, reports have commented that energy efficiency measures to improve commercial buildings can increase productivity levels and improve the health and wellbeing of workers (WSBF 2013; World Green Building Council 2013). However, it is also recognised in the reports that further research is required to make these benefits more credible. One challenge of designing buildings to more stringent energy standards and reducing infiltration is the greater dependency on purpose-driven or controlled ventilation to achieve and maintain adequate IAQ. Without necessary attention to purpose-driven ventilation, greater airtightness of the building envelope which is required to improve energy efficiency in buildings could result in ventilation rates which are lower than the minimum specified and this will in turn have adverse consequences on indoor air quality. This will be particularly important in buildings where infiltration provides beneficial, additional ventilation to dilute of indoor air pollutants.

Parameters that affect the indoor environment (temperature, relative humidity, and indoor air pollutants) are all interrelated and they need to be taken into account during design, construction and use of the building. These parameters are influenced by factors such as the weather, the building envelope, the ventilation system and the occupants (presence and activities). Some key principles of this relationship were summarised by Rousseau (2003):

- *Higher insulation levels to reduce heat losses and heating costs and increase comfort will increase the likelihood of condensation forming inside the insulated* *wall and ceiling cavities. Accumulated moisture can lead to rot, mould growth and reduced insulation performance.*

- *To reduce heat losses by air leakage a continuous air barrier incorporated in the insulated walls can have the benefit of reducing entry of outdoor air pollutants. However moisture and pollutants generated indoors will remain in the building longer unless removed by suitable ventilation*
- *Indoor air pollutants and, to some degree, moisture are best handled through source control. This can be done by continuous operated, mechanical ventilation systems. However these systems expend energy and when not maintained appropriately can also be a source of pollution.*

Some research has been conducted to investigate the implications of new energy efficient homes on occupants. Bone *et al*. (2010) examined the changes in UK homes and the possible consequences for health and noted that measures to improve energy efficiency and thermal comfort, both in new build and through refurbishment of existing housing stock, have the potential to substantially reduce air permeability. They also commented that with the expectation of more frequent and more intense heat waves, improved insulation may prevent heat gains from escaping thus increasing heat related health risks. Jenkins *et al*. (2009) simulated the impact of future small power, lighting energy and a warming climate on future low-carbon schools to quantify the risk of overheating. They concluded that increasing ventilation and external shading may be required to reduce the risk of overheating. In offices, there is lack of information on the concerning impacts of energy efficiency measures but as summarised in the report by Rousseau *et al.* (2003), increasing airtightness and reducing infiltration to reduce heat losses can pose increasing concern for the quality of air in indoor spaces and so, appropriate purpose-driven ventilation systems have to be considered and further studies are required to investigate the impact of building energy measures, such as increasing airtightness and reducing infiltration, on occupant comfort and health.

2.2 Recommended standards for indoor environments

Characteristics of the indoor climate in buildings are described in terms of temperature and indoor air quality. Limits are set on environmental variables for different spaces with the aim of protecting the health and wellbeing of occupants. The ASHRAE Standards 55 and

62.1 (ASHRAE 2010a; ASHRAE 2010b), CIBSE Guide A on environmental design (CIBSE 2006) and the European Standard on thermal comfort and indoor air quality, EN15251 (CEN 2007b) are internationally recognised standards that specify the conditions for indoor environments. These standards specify categories of criteria that may also have significant influences on building energy demand. The ASHRAE Standard 55 which specifies a combination of indoor environmental and personal factors that provides acceptable thermal conditions (ASHRAE 2010a) is based on Fanger's heat balance model (Fanger 1970) and it also includes an adaptive comfort standard that specifies higher indoor temperatures in naturally ventilated buildings.

2.2.1 Thermal comfort and the adaptive approach

Thermal comfort is associated with the need to maintain a stable core body temperature and is affected by environmental parameters (e.g. temperature, air velocity, and relative humidity), personal parameters (e.g. clothing and activity levels), building parameters and surrounding environment. The widely known laboratory experiments conducted by Fanger (1970) were to determine the indoor thermal conditions required for thermal comfort. These studies were based on the assumption that thermal comfort was related to the human body. In his studies, participants were exposed to purposefully varied conditions in climate chambers in which their clothing levels and activity levels were controlled. Using results from these experiments, Fanger developed the heat balance model which is a method of measuring thermal comfort, in the form of the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). The predicted mean vote is defined as an index that predicts the mean response of a large group on a thermal sensation scale and the predicted percentage dissatisfied is an index that establishes a quantitative prediction of the of the percentage of the group of people who are thermally dissatisfied (ASHRAE 2010a). The heat balance model combines the effects of the environmental and the personal parameters to predict comfort response of occupants and determine the percentage of occupants who are dissatisfied with the environment. However, this method and the results have been criticised as the controlled conditions do not reflect real life environments and do not take into considerations factors such as cultural and social differences in occupants (de Dear 2004). Fanger's initial work was geared towards mechanically ventilated buildings where it is necessary to have well controlled indoor environments. Later, Fanger and Toftum (2002) attempted to extend the PMV model to non-air-conditioned buildings and they found that the model overestimated the sensation of warmth in non-air-conditioned buildings in warm climates. The suggested explanation given was that occupants in warmer climates may perceive the warmth as less severe than the model predicts. They proposed that the PMV model should include an expectation factor to make it applicable to non-air-conditioned buildings. They also addressed the notion of the PMV model being referred to as a static model (i.e. prescribing one constant temperature as the comfort temperature) and disregarded that claim, saying that the model may predict temperatures between 10 and 35°C as the comfortable temperature, depending on the other variables in the model.

The adaptive principle or adaptive approach to thermal comfort as defined by Nicol and Humphreys (2002) states that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". This was developed from field studies, observing occupants in daily life. Nicol and Humphreys developed this approach based on the fact that the adaptive method is a behavioural approach and that occupants will make themselves comfortable by adjusting themselves or their environment given time and opportunity (Nicol & Humphreys 2007). This implies that unlike the heat balance model, occupant's interaction with the environment will also affect their thermal comfort.

The ideal temperature for a space is dependent on its intended use and the recommended temperatures (given in the standards) are derived from calculations based on the activity of the occupants in the space and their clothing levels. In the UK, the Workplace Health and Safety Regulations (HSE 2004) require that the minimum, but not comfort, indoor temperature to be at least 16°C. For offices, most guidelines suggest a range of 20-25°C. For mechanically ventilated offices the recommended design temperatures for summer and winter are 20°C (range: 20-24°C) and 26°C (range: 23-26°C) respectively (CEN 2007b). In naturally ventilated offices, acceptable indoor temperatures are dependent on outdoor temperatures. Figures 2-1 and 2-2 present acceptable temperature ranges specified by ASHRAE 55 and EN 15251 respectively. The ASHRAE standard defines ranges of temperatures in zones in which 80% and 90% of occupants are expected to be satisfied with the environment and the EN15251 standard describes the buildings in different categories: Category I – high level of expectation, recommended for spaces occupied by very sensitive persons, Category II – normal level of expectation, Category III – acceptable to moderate level of expectation (CEN 2007b). From the charts, it can be seen that the ASHRAE standard predicts slightly lower indoor temperatures at lower outdoor temperatures than the European standard. Nicol *et al*. (2012) explain that the difference in the acceptable indoor temperature ranges between the two standards is because they are based on two different survey studies from different buildings, by different research teams using different instruments and different methods of analysis. A standard for overheating is specified for different premises and in offices, CIBSE Guide A (2006) defines that the indoor temperature should not exceed 28°C for 1% of the annual occupied hours. Thermal comfort and overheating may change with the adaptive approach and so these recommended standards are not absolute values.

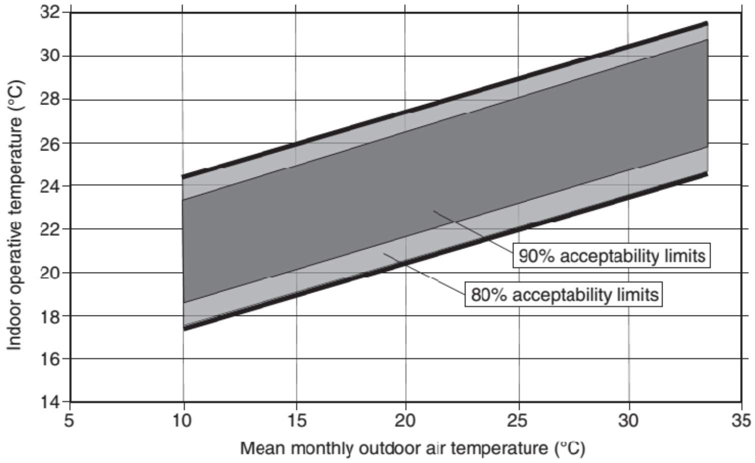


Figure 2-1: Acceptable operative temperature ranges for naturally conditioned spaces (Source: ASHRAE Standard 55-2010).

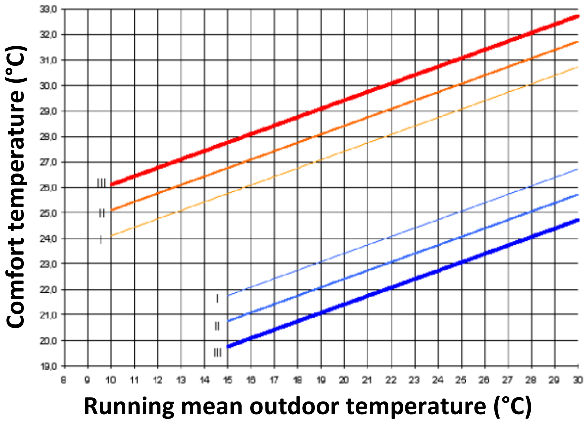


Figure 2-2: Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature (Source: EN15251)

Noise levels are also specified as different noise level affects the comfort of people in different situations, causing interference to speech and hearing as well as annoyance. It does not affect thermal comfort, however, it is an important parameter to consider as it may affect how occupants control their indoor environments using windows. EN15251 (2007b) and CIBSE Guide A (2006) recommend sound levels in the range of 30 to 45dBA for office environments, depending on the type of space (e.g. single offices or open place spaces). These values can be exceeded when windows are used and the European standard makes it clear that adequate ventilation should not depend on window opening alone as factors such as excessive noise levels can prevent occupants from opening windows. National guidelines also provide guides on noise levels at the work place depending on the type of work being conducted.

2.2.2 Parameters of IAQ

Indoor air quality (IAQ) is a subject of occupant comfort and health because of the amount of time we spend indoors. Acceptable IAQ is defined as “air in which there are no known contaminants at harmful concentrations as determined by cognisant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction” (ASHRAE, 2005). In the CIBSE Guide A (2006), the definition has been further summarised in four points, that for comfort, indoor air quality may be said to be acceptable if:

- *Not more than 50% of the occupants can detect any odour*
- *Not more than 20% experience discomfort*
- *Not more than 10% suffer from mucosal irritation*
- *Not more than 5% experience annoyance for more than 2% of the time*

Although the third point is potentially health related, these criteria are primarily comfort-based and hence do not take into account the potential health effects of poor indoor air quality. The CIBSE Applications Manual defines the principle role of ventilation as to provide an appropriate level of indoor air quality by removing and diluting airborne contaminants (CIBSE 2005).

Ventilation rates required for air quality are also specified depending on occupant density, activities and pollutant emissions in the space. Ventilation is specified for different classifications of indoor air quality standard (high, medium, moderate and low). Minimum ventilation rate varies internationally. Table 2-1 presents typical minimum ventilation rates recommended by Building Regulations and standards.

Table 2-1: Recommended minimum ventilation rates

Standard	**Recommended minimum ventilation rate (L/s/person)**	**Comments**
ASHRAE (2010b)	4 - 10	For education facilities and office buildings
UK Building Regulation: Part F (Building Regulation 2010)	10	For non-domestic buildings – provided the indoor air is relatively free from pollutant sources and the ventilation air is pure
European Standard (CEN 2007a)	6 – 10 (default value = 8) 10 – 15 (default value = 12.5)	For moderate indoor air quality For medium indoor air quality

The description of the indoor air classifications depend on the nature of the pollutant sources in the room and the effects on the occupants. The ventilation rates relate to comfort air quality and odour and they are based on laboratory and field studies which showed that for sedentary occupants about 7.5L/s per person of outdoor air will dilute odours to levels that will satisfy 80% of people entering the room (Fanger & Berg-Munch 1983; Berg-Munch *et al.* 1986). Olesen (2011) explains that the difference between the European and ASHRAE standards is because the basis for design for ASHRAE is adapted people (occupants who are already acclimatised to the space) while for the European recommendation it is un-adapted people (visitors).

Concentrations of indoor air pollutants also reflect on the indoor air quality with regard to sensory irritation and odours. The recommended levels are proposed for both domestic and industrial buildings by several national and international organisations (e.g. WHO, NIOSH, OSHA). They set limits such as threshold limit values and permissible exposure limits for several pollutants. Tables of concentrations of the pollutants and comparisons of regulations and guidelines are presented in ASHRAE 62.1 (ASHRAE 2010b). Pollutants such as carbon monoxide and formaldehyde are considered.

Indoor relative humidity in the range of 40% to 70% is specified by building standards as generally acceptable (CIBSE 2006). This wide range is due to the fact that humidity has little effect on feelings of warmth particularly for sedentary, lightly clothed occupants. It becomes apparent at high temperatures when it affects thermal comfort by hindering sweating.

Carbon dioxide (CO_2) is an indoor pollutant and guidelines for occupational exposure to CO_2 are defined by various Health and Safety organisations (e.g OSHA 2012; HSE 2011). In the UK, the workplace exposure limit for an 8-hour workday is 5000ppm and for a 15 minute period, it is 15,000ppm (HSE 2011). The minimum ventilation rate recommended by the UK Building Regulation and ASHRAE corresponds to an indoor CO_2 concentration of 1500ppm (Building Regulation 2010; ASHRAE 2010b). The impact of carbon dioxide on occupants will be discussed in more detail in Section 2.2.6.

2.2.3 Sources of indoor air pollution

Sundell (2004) provided a review of the history of indoor air quality and discussed that initially it was thought that occupants were the sole pollution source in indoor environments. It has now being recognised that other pollution sources other than those emitted by humans are equally important. Sources of indoor air pollution can be divided into three categories: polluted outdoor air entering the indoor space, occupants and their activities and pollution-emitting products within the indoor space. Depending on the location of the building, outdoor air entering the building could be exhaust gases from cars, emissions from industrial processes and gases from the soil (radon). Within the indoor space, occupants' exhalation and activities common in dwellings (e.g. cooking, smoking and drying clothes) are sources of pollution and moisture. Building materials, furnishes and chemical products can also be sources of indoor pollution. Table 2-2 gives a summary of the sources and types of pollutants found in indoor spaces. Pollutant sources such as pets and washing are usually associated with dwellings and in the UK HVAC systems are usually associated with commercial buildings. Building materials and furnishing materials emit pollutants regardless of human presence or activity. New building materials and furnishing materials are considered to have an important role for indoor air quality as they also act as storage areas for pollutants such as particles and gases from other sources (Šeduikyte & Bliūdžius 2005).

Table 2-2: Sources and types of indoor air pollution (Crump *et al.* 2009)

Category	**Source**	**Pollutant**
From outdoor air	Outdoor air	SO_2, NO_x, ozone, biological particulates
	Ground	Radon, moisture
Occupants and their activities	People	CO_2, organic compounds, odours, biological particulates
	Washing and cleaning	Moisture
	Environmental Tobacco Smoke (ETS)	CO, VOCs, particulates
Pollutants indoors	Building materials	VOCs, formaldehyde, asbestos, particulates
	Furnishings and paints	VOCs, formaldehyde
	Pets and other animals (mites)	Allergens, viruses, bacteria
	Consumer products	VOCs, formaldehyde
	Office equipment	VOCs, ozone
	Ventilation systems (HVAC)	VOCs, particulates

The indoor air pollutants are in gaseous, particulates or microbial forms and can enter bodies through the nasal passage or can be felt on the skin, making occupants uncomfortable or ill. Substances that enter the nasal passage may be sensed through the olfactory sense (odour) and/or as an irritant sensation (e.g. eyes, skin). They can also exhibit as allergic reactions. According to the CIBSE Guide A, there are two kinds of adaptation to odour: over periods of 30 minutes, occupants become less sensitive to the odour present in the space and in weeks or months, they become less aware of the odour, accepting it as normal and harmless.

Volatile organic compounds (VOCs) and formaldehyde are associated with building and furnishing materials (e.g. foam insulation and paints), environmental tobacco smoke, electrical products (e.g. computers and printers) and consumer products (e.g. cleaning products, aerosol sprays and, textiles). VOCs and formaldehyde are common chemical contaminants which are a source of odours. They can therefore cause irritation when inhaled. Exposure limits to VOCs are set by standards and legislation because of their impacts on occupant health and well-being.

Radon is a naturally occurring radioactive gas that is drawn into buildings from the underlying rocks and soil surrounding the building's foundation and from groundwater sources. It is colourless and odourless but a carcinogen which is known to cause lung cancer. It can be drawn into the indoor space through infiltration and can accumulate to high, dangerous levels in poorly ventilated buildings.

Particulates such as PM_{10} and $PM_{2.5}$ (particulate matter with aerodynamic diameters of 10µm and 2.5µm respectively) are commonly found in indoor air as they are associated with a wide range of sources (both inside and outside the building). Due to the very small size of these pollutants, they stay in the air for long periods of time and are easily inhaled, causing irritation of the respiratory tract.

Relative humidity above 70% can lead to issues with mould and mildew growth and also growth in house dust mites, particularly in homes. Moisture and mould growth are pollutants which cause health problems including increasing asthma attacks and respiratory allergies. Mould grows in steady state conditions so once established can continue to thrive at lower humidity levels. Increasing indoor humidity levels usually occurs through evaporation from moisture sources (e.g. wet clothes) and condensation as a result of poor ventilation. High relative humidity levels are mostly common in bathrooms and kitchens in homes and low RH levels are common in heated buildings (during the winter season). Low humidity is also associated with irritation of the respiratory tract such as dryness and reduction in mucous flow which inhibits the dilution of irritant contaminants.

Carbon dioxide, organic compounds and body odour are indoor pollutants produced by humans. They can be used as an indication of the presence of occupants in an indoor space.

2.2.4 Ventilation and IAQ

Sections 2.2.2 and 2.2.3 highlight the different parameters that affect the indoor air quality. Ventilation also has an effect on indoor air quality. There is increasing evidence that increased ventilation rates and resulting improved air quality will have increased health and performance benefits in children and office workers (e.g. Wargocki *et al.* 2000; Bakó-Biró *et al.* 2007). These benefits have been investigated in homes, schools and at work places and some have been quantified.

2.2.4.1 Impact on performance

Wargocki *et al*. (2000) conducted controlled experiments and demonstrated that increased ventilation rates and improvement in indoor air quality has positive impacts on office work performance. Repeated experiments were carried out for ventilation rates of 3, 10 and 30 L/s per person. For every increase in ventilation rate, they noted that performance improved on average by 1.7%. Increasing ventilation rates also increased participant's perceived freshness of air and decreased the percentage of participants dissatisfied with the air quality. Haverinen-Shaughnessy *et al.* (2011) investigated the association between classroom ventilation rates and academic achievement in 100 elementary schools in the US. They measured the ventilation rates using CO_2 concentrations measured during occupied school days. The recorded CO_2 concentration ranged from 661 to 6000ppm and the ventilation rates estimated ranged from 0.9 to 11.7 L/s per person. Standardised test scores were collected for the pupils in the classrooms during the measuring period. Analysis was performed on data from schools that estimated ventilation rates below 7.1 L/s/person. Their research suggested a linear association between ventilation rate in the classrooms and student test scores. For every 1 L/s/person increase in ventilation rate, the proportion of students passing the standardised test was expected to increase by 2.9% for maths and 2.7% for reading. The impact of ventilation rate on school work performance was again observed by Bako-Biro *et al*. (2007) in a number of primary schools in the UK. In this study, indoor environmental variables were monitored and performance tests were administered to the pupils in the monitored classrooms. Alongside these, subjective evaluations of the environmental perception, comfort and health were provided by the pupils. The study found a significant impact of ventilation rate on school work performance. The overall performance was observed to increase when ventilation rate was increased from approximately 0.4 to 14.5 L/s per person. Improvements of 5.1% and 5.8% in addition and subtraction respectively were observed and this effect was found to be higher in pupils with higher maths abilities. This study suggests that there is a trend approaching significance towards higher alertness, better work mood and tendency for less tiredness and increased attention following the performance tests conducted at higher ventilation rates. These findings are in line with other findings that show that improved indoor environment has beneficial effects on pupils' performance. Mendel and Heath (2005) carried out a review of school environments and performance to summarise the available knowledge relevant to effects of schools indoor environments on performance and attendance of pupils. They suggested that evidence of certain indoor conditions found in schools have adverse effects on the health and academic performance of school children. Conditions such as temperature and indoor pollutants were found to have negative effects on children's performance and attendance. These factors were statistically significant in causing the effect.

2.2.4.2 Impact on health

Building related illness refers to illnesses that are caused directly as a result of being in a building and are caused by a combination factors which includes biological and chemical (e.g. pet furs, bacteria and organic compounds from occupants and VOCs) and physical factors (e.g. temperature, heat and noise). They are often grouped into two categories: those caused by exposure to identifiable sources (e.g. asbestos) and those with no readily known cause. The latter is usually described in terms of symptoms known collectively as sick building syndrome (SBS) symptoms. The symptoms associated with SBS are (Jones 1999):

- Eyes – irritation, itchy, dry, watery
- Nose – irritation, itchy, runny, dry, blocked, difficulty in breathing, sensitivity to odours
- Throat – sore, constricted, dry mouth, coughing
- Head – headache, lethargy, irritation, dizziness, difficulty in concentration, fatigue
- Skin – dry, itchy, irritation, dermatitis

The intensity of the symptoms tends to increase with the time spent in the building and improve or disappear when the culprit building is evacuated. There is no single known cause of SBS but there are several factors which are attributed to the prevalence of the symptoms and have been identified through field and experimental studies (e.g. Fang *et al.* 2004). These symptoms are now usually used to assess the indoor air quality.

Building materials, furnishes, chemical products and occupant presence and activities are all sources of indoor air pollutants. Improvements in construction technology have led to the use of more synthetic building materials and furnishings and consumer products such detergents have also led to the introduction of many different sources of chemicals into the indoor environments. Indoor air may contain over 900 chemicals, particles and biological materials with irritating and sensitizing potential (SCHER 2007). Because of limited indoor space, concentrations of these pollutants can be higher than that outdoors and as we spend a significant amount of time indoors, exposure to indoor pollutants can cause a variety of effects on occupants. It has been suggested that exposure to pollutants are related to comfort and health issues reported in schools, offices and homes (Daisey *et al.* 2003). Exposure and symptoms have been simultaneously investigated to indicate these relationships.

A review on ventilation rates and health suggests that ventilation rates of up to 25 L/s per person are associated with reduced sick building syndrome symptoms and respiratory illnesses in children (Sundell *et al.* 2011). With airborne infectious diseases, the risk of spread of infection is related to ventilation rates. A study in a jail showed an association between inadequate ventilation and an outbreak of pneumococcal disease (Hoge *et al.* 1994) and the presence of recirculation of air was found to increase attack rates of influenza (Drinka *et al.* 1996). The conclusion made in a review of the role of ventilation in airborne transmission was that there is strong and sufficient evidence showing a link between ventilation and the spread of infectious diseases such as measles, tuberculosis, chicken pox, small pox, influenza, anthrax and SARS (Li *et al.* 2007).

In the Netherlands, a study was conducted in primary school buildings where the children's home environment was also taken into account (van Dijken *et al.* 2006). The aim of the study was to assess the association between indoor environmental quality and pupils' health. Nasal and respiratory symptoms and general ill health symptoms were linked to pollutants such as environmental tobacco smoke, mould growth and dampness and pollutants found in the school such as high concentration of particulate matter and dust sources. Another study carried out by Kim *et al.* (2007) in schools found an association between exposure to microbial volatile organic compounds (MVOCs) and asthma and other respiratory symptoms in pupils. This association was stronger in schools with lower air exchange rate, indicating an association between ventilation and IAQ and health.

A study was carried out in 390 Swedish homes to research the association between low ventilation rates and increased prevalence of asthma and allergic symptoms in children (Bornehag *et al.* 2005). This study found that a significant proportion of the homes studied did not fulfil the minimum legal requirements for air change rate. It suggested that low ventilation could be a risk factor in increasing symptoms in children. Studies in homes with damp issues have also reported higher prevalence of respiratory diseases such as asthma (Lindfors *et al.* 1995; Williamson *et al.* 1997). Other environmental factors that were reported to be associated with the risk of asthma were exposure to environmental tobacco smoke and allergens from furred pets. Another study was carried out to investigate the concentration of house dust mites in 96 Danish homes with member(s) suffering from asthma (Harving *et al.* 1993). A significant correlation was found between indoor air humidity and mite concentration and also between house-dust mite concentration and low ventilation rate. High concentrations of house-dust mites were found in 76% of the homes with members with mite allergies. These studies all indicate that due to the rapid increase in the prevalence of asthma and allergies in recent decades, attention needs to be given to environmental changes and not just genetic factors.

Investigations in office buildings revealed an association between increasing levels of indoor CO_2 concentration and some SBS symptoms (Apte *et al.* 2000). This study suggested that increases in ventilation rates will, on average, significantly reduce the prevalence of several SBS symptoms, even when buildings meet minimum ventilation standards. This result is consistent with other research carried out in office buildings which found that the risk of SBS symptoms increased significantly with decrease in ventilation rate (Stenberg *et al.* 1994; Sundell *et al.* 1994). A study by Jaakkola *et al* (1991) also concluded that decreasing ventilation rate increased the prevalence of SBS symptoms. Their conclusion was as a result of an epidemiological study in an office building and it also suggested that indoor air temperature and relative humidity are important determinants of SBS symptoms.

Environmental factors such as ventilation rates and occupancy patterns can be used to examine the impact of airborne infection transmission. Noakes *et al.* (2006) integrated classical epidemic models with environmental factors such as ventilation rate and occupancy to examine the impact of changes in the physical environment on airborne infection transmission in enclosed spaces. Their results suggested that increasing ventilation can reduce the rate of infection as well as removing the potential of an epidemic all together.

Milton *et al*. (2000) found consistent associations between increased sick leave and lower levels of outdoor air supply rate in office workers. In their study, they specified ventilation levels of 12 L/s per person (moderate) and 24 L/s per person (high) and showed that the reduction in sick leave rates associated with increased ventilation rate was similar to the reduction in sick leave observed during the flu season with vaccination. From their results, they also demonstrated an economic cost of sick leave due to ventilation at the current recommended rate of 10 L/s per person. They suggested that with current recommended ventilation rates, lost productivity due to sick leave could cost as much as $22.8 billion per year. A recent study done in this area also estimated an annual economic benefit of $13 billion from increasing minimum ventilation rate from 8 to 10 L/s per person and $38 billion from increasing minimum ventilation rate from 8 to 15 L/s per person. In this study, the benefits of increasing minimum ventilation rate far exceeded energy cost. An estimated $0.04 billion was noted for annual energy-related benefits from decreasing minimum ventilation rate from 8 – 6.5 L/s per person (Fisk *et al.* 2011; Fisk *et al.* 2012). These indicate that improvement in ventilation rates and indoor environment quality will have far reaching benefits – prevent symptoms of ill-health and absences from work and school as well as significant economic benefits.

2.2.5 Summary on standards for indoor environments

Standards for the indoor environments and the impact of factors of the indoor environment have been presented and discussed. The wide variety in factors that affect occupant comfort and health (thermal comfort and IAQ parameters) indicate the importance of both controlled and uncontrolled ventilation. For instance, due to the nature of indoor pollutants (e.g. small size, odourless, colourless) and the fact that detection of odours is reduced within a short period of time, provision of adequate ventilation should be a priority. Increased airtightness and reduced infiltration becomes an issue when adequate ventilation is not achieved. As mentioned in the section above, some earlier studies suggests that ventilation rates more than double the current recommended rate may be required to reduce the health impacts of poor indoor air quality. It is important for designers and occupants to make sense of the many requirements of the indoor environment in providing and attaining comfortable and healthy as well as energy efficient indoor environments. For researchers and designers, there is a need to shift the focus from trying to predict a small range of comfort temperature to trying to understand how occupants react to their environment and how they use adaptive measures such as opening a window not only for thermal comfort but also for adequate indoor air quality. It is also important to try and understand how interactions between the different elements of the indoor environment influence occupant adaptive behaviour. For instance what is the relative importance of external noise and temperature or indoor air pollutant and temperature on occupant adaptive behaviour?

2.2.6 CO_2 concentration in indoor spaces

Carbon dioxide concentration occurs naturally in the atmosphere with recent typical outdoor levels of approximately 400ppm (0.04%) (Scripps CO_2 Program 2014). CO_2 is also one of the by-products of respiration which humans exhale at a rate of 0.31 L/min (for an adult doing light to medium work) (ASHRAE 2010b). CO_2 is regarded as one of the indoor pollutants and in gaseous state, it is odourless and colourless. In an occupied space CO_2 concentration can be greater than the concentration outside. Prior research has shown direct health effects of CO_2 on occupants, with symptoms ranging from drowsiness and headache (e.g. Seppänen *et al.* 1999) to death (e.g. Dunford *et al.* 2009). The latter effect has been observed when CO_2 concentrations is in the order of tens of thousands parts per million (ppm).

There have been several reports of the effects of exposure to extremely elevated levels of CO_2 on humans due to occupational exposure and environmental releases and the effects have been unconsciousness, induced coma and in some cases death. Dunford *et al*. (2009) reported the case of a healthy 59 year old man who was found collapsed inside a closed freezer. Upon opening the freezer door, investigators found blocks of dry ice placed in coolers with lids that did not latch. Measurements taken with a gas indicator showed a reading of 25,000ppm (2.5%) of CO_2 (upper limit of the instrument) and the investigators estimated that the CO_2 levels inside the freezer could be as high as 40%. Unfortunately resuscitative and advanced life support efforts were not successful and the victim was pronounced dead with the cause recorded as asphyxiation due to exposure to CO_2. In 1986, environmental release of CO_2 was responsible for causing the deaths of 1700 people as well as animals (including fish in the lake) in Cameroon, West Africa (Baxter *et al.* 1989). This was due to a substantial release of CO_2 from Lake Nyos, a volcanic crater lake. The atmospheric CO_2 was estimated to be up to 10%. An interviewed survivor revealed that when he woke up, he was not able to stand up and he was confused (BBC World Service 2011). Scientists believe that those who survived must have been unconscious for hours during the night until the CO_2 gas suspended in the air begun to lift in the morning. Survivors within 3 to 10km of the lake reported fatigue, light-headedness, confusion, dizziness and shortness of breath prior to unconsciousness. Other symptoms which were presented by survivors for two weeks after the incident were headache, cough, weakness and eye symptoms and these were attributed to variations in and exposure to CO_2 concentration (Rice 2004). Although death due to exposure to CO_2 is usually attributed to asphyxiation, there is data suggesting that other biological mechanisms might be involved. The effects of CO_2 on the body increase as concentration and time of exposure increase.

The National Institute for Occupational Safety and Health (NIOSH) has documented a summary of studies investigating the effects of acute, intermittent and chronic exposures to CO_2 on humans (NIOSH 1976). In the studies reviewed, participants were exposed to CO_2

concentrations ranging from 0.03% to 30%. For acute exposure (CO_2 concentrations of 17% to 30%), participants were exposed to CO_2 administered through a gas mask. Observations showed effects such as depression of the central nervous system, narcosis, increase in respiration rate and increase in systolic and diastolic blood pressure. Participants tolerated the conditions for an average of 37 seconds before loss of consciousness. To study the effects of intermittent exposures (CO_2 concentrations increasing from 0.03% to 3% in 12 to 15 hours), a gas chamber was used as the exposure method and some of the effects observed were increase in human ventilation rate, metabolic acidosis and CO_2 removal through renal mechanism. For chronic exposures to CO_2 (five day continuous exposure to CO_2 concentration of 3%) spaces representative of space cabins and submarines were mainly used as the exposure method. The effects observed included increase in alveolar CO_2 levels, lowered respiratory sensitivity, reduced ability to perform strenuous exercise and evidence of increased airway constriction.

It is worth mentioning that indoor levels are lower than levels measured in the incidents described above. However, indoor levels may also impact on occupant health. In Sundell's review on the history of indoor air quality and health, he comments that in the early 19th century it was accepted that concentration of CO_2 was a measure of fresh or stale air (Sundell 2004). In the review he noted Max Joseph Pettenkofer's (1818-1901) view that air was not fit for breathing if the CO_2 concentration was above 1000ppm (0.1%) and that good indoor air in rooms of prolonged occupancy should not exceed 700ppm (0.07%) in order to keep the occupant comfortable. Since then, several studies have been conducted in homes, schools and offices to investigate the effects of exposure to low-to-moderate levels of CO_2 (Norbäck *et al.* 1995; Daisey *et al.* 2003; Satish *et al.* 2012). The methods used in these studies have been either controlled experiments or direct measurement of CO_2 concentration in the space.

2.2.6.1 CO_2 in homes

Due to the increased concern over the negative health effects of indoor air pollution in dwellings, Norbäck *et al.* (1995) carried out a survey as part of the European Community Respiratory Health Study to establish relations between symptoms of asthma, building characteristics and indoor air quality. In their survey, they measured indoor air parameters including room CO_2, VOCs, and formaldehyde in a number of dwellings selected by stratified random sampling in an urban community in Sweden. The residents of these dwellings underwent structured interviews and medical tests. From their results, they showed that CO_2 concentration was significantly higher in the homes of those who reported nocturnal chest tightness (1020ppm) compared to homes which did not report symptoms (850ppm).

2.2.6.2 CO_2 in schools

In a field survey, Myhrvold *et al.* (1996) investigated the relationship between CO_2 concentration and pupils' health and performance. The project involved 35 classrooms and about 800 pupils from eight schools. The environmental parameters measured included air temperature, humidity, air velocity and air content of CO_2 and VOC. The pupils were asked to complete a questionnaire survey and a concentration test. The mean CO_2 concentration at daytime ranged from 601 to 3827ppm and the readings were put into three groups (0 – 999ppm, 1000 – 1499ppm and 1500 – 4000ppm). The results showed correlations between CO_2 concentration and pupils' health and performance. Some of the health symptoms reported were headache, dizziness and difficulties in concentration. The number of symptoms reported increased significantly when CO_2 concentration increased from 0–999ppm to 1000–1499ppm to 1500-4000ppm. The correlation between CO_2 and performance was also significant, with a decrease in performance with increasing CO_2 concentration. An analysis of indoor air quality in schools showed that a significant proportion of classrooms did not meet the requirements for CO_2 levels (Daisey *et al.* 2003). The CO_2 concentrations ranged between 500ppm and 5000ppm. A study on ventilation rates and learning performance in schools recorded CO_2 levels up to 4000ppm during the school day (Bakó-Biró *et al.* 2012). These high levels of CO_2 in classrooms have been found to reduce the ability of students to concentrate and it has also been associated with a decrease in attendance (Coley & Greeves 2004; Shendell *et al.* 2004). A study on health effects of school environments was conducted in five European countries by Simoni *et al.* (2010). The study showed that 66% of school children were being exposed to CO_2 levels greater than 1000ppm. CO_2 concentration measured in the classrooms ranged from 525ppm to 3475ppm. Symptoms of dry cough and rhinitis were more prevalent in children who were exposed to CO_2 levels above 1000ppm and the higher risks for these symptoms were statistically significant. Significant positive associations of dry cough at night and rhinitis were found with 100ppm increments in CO_2 concentration. The poor indoor air quality in European countries was linked to respiratory disturbances in children. In university computer classrooms, an investigation was conducted to study the effects of CO_2 demand-controlled ventilation (Norbäck *et al.* 2012). The ventilation modes used were demand-controlled variable flow and constant flow. The demand-controlled ventilation system was designed to increase ventilation flow when CO_2 levels were above 800ppm. The mean CO_2 level was 809ppm at constant flow and 784ppm at variable flow conditions. The results showed statistically significant, but numerically small, differences in favour of variable flow conditions for perception of indoor air quality, headache and tiredness. The study was carried out in four classrooms. It was experimental and the ventilation conditions were blinded to the participants. This highlights that small changes in CO_2 levels can have an impact on symptoms and perceptions of the environment.

2.2.7 CO_2 in offices

In an investigation of indoor air quality complaints in the Air Force, Carpenter and Poitrast (1990) established a database of measures of CO_2, relative humidity (RH), organic vapours and the symptoms associated with them from approximately 75 buildings over a four year period. Their approach consisted of simultaneous assessments by a health care provider, a public health officer and an industrial hygienist. Standardised questionnaires were used in eight of the buildings and standard medical interviews were conducted in the remainder of the buildings. To quantify as a symptom, a worker must have at least one symptom which appeared at least once a week and the symptom should be reported at least once – three days per week during the study period. The workers should also report that the symptom goes away when they are not in the building. The investigators observed that symptoms of fatigue, drowsiness, dizziness, increased ear, nose and throat problems and a tendency for increased headache and problems breathing were correlated with increased CO_2 and decreased RH. Results from these two experimental procedures were analysed statistically and a theoretical model was determined based on several assumptions to clarify the observations. The model showed that at 600ppm, some parts of the population begin to experience some level of fatigue. From their experience, they confirmed that between 15% and 33% of the population will have symptoms at CO_2 concentrations between 600ppm and 800ppm; 33% to 50% will have symptoms between 800 and 1000ppm and over 70% will have symptoms at CO_2 levels above 1500ppm.

A review on associations of ventilation rates and CO_2 with health showed that CO_2 concentrations in office buildings typically range between 350 to 2500ppm (Seppänen *et al.* 1999). In this review, 11 out of the 22 available studies reported a statistically significant positive association between CO_2 concentration and sick building syndrome symptoms. Sick building syndrome symptoms associated with increase in CO_2 included headache, fatigue, eye symptoms and nasal symptoms. Researchers also analysed data from a 100 building dataset to assess the association between indoor carbon dioxide concentrations and sick building syndrome symptoms in U.S. office buildings (Apte *et al.* 2000; Erdmann *et al.*

2002). In these studies, the difference between indoor and outdoor CO_2 concentration during the workday was calculated (dCO_2) and the results showed statistically significant associations between some mucous membrane symptoms and lower respiratory symptoms and increase in dCO_2. The odds ratio for significant associations of symptoms with 100ppm and 250ppm increase in dCO_2 was up to 1.5 and 2.3 respectively indicating that occupants exposed to increasing levels of CO_2 concentration were more likely to report symptoms. In their study to investigate the effect of lower ventilation rates on sick leave, Milton *et al.* (2000) recorded average CO_2 concentrations of 800-900ppm when the ventilation rate was "moderate" (11-13 L/s per person) and 600ppm when the ventilation rate was "high" (23L/s per person). These ventilation rates are higher than the recommended ventilation rates provided by building regulations and standards but it is clear that even at these ventilation rates, CO_2 levels associated with sick building syndrome can occur.

Tsai *et al.* (2012) also made an attempt to determine an association between sick building syndrome (SBS) and indoor CO_2 concentrations. In their study they measured environmental parameters including CO_2 levels, temperature and relative humidity and simultaneously asked a group of 121 workers to report self-diagnosed SBS symptoms in a questionnaire. The SBS symptoms were categorised into five groups: eye irritation, upper respiratory symptoms, lower respiratory symptoms, skin irritation and non-specific symptoms. The non-specific symptoms category included headache, difficulty in remembering or concentrating and unusual tiredness. Their results showed that workers exposed to CO_2 levels of greater than 800ppm were more likely to report symptoms of eye irritation, difficulty in remembering or concentrating and upper respiratory symptoms compared to those exposed to less than 500ppm of CO_2. The prevalence of headache symptoms was marginally increased when CO_2 levels was greater than 800ppm. They conclude that indoor CO_2 levels greater than 800ppm is associated with an increase in workers' SBS symptoms.

Kajtar *et al.* (2003) conducted a study to examine the influence of indoor CO_2 concentration on human well-being and the intensity of office work. These studies were carried out in an experimental chamber where four different CO_2 concentrations were pre-set (600, 1500, 3000 and 4000ppm). The study comprised of 10 participants with each experiencing the four environmental conditions created. Participant well-being and comfort were evaluated using questionnaires and their mental performance was measured using a standard test which involved reading a text. The performance was characterised by the number of rows read and the percentage of misspelled words identified. Results from the questionnaires showed that participants evaluated the air with 3000 and 4000ppm of CO_2 as significantly less acceptable than air with CO_2 levels at 600ppm and 1500ppm. Results from the performance test also showed that there was a significant difference in the percentage of misspelled words found in CO_2 concentration of 600 and 3000ppm and in 600 and 4000ppm. This study concludes that human well-being and capacity to concentrate attention declines when CO_2 concentration increases up to 3000ppm.

Similarly, researchers at the Lawrence Berkeley National Laboratory found that moderate levels of CO_2 can significantly impair occupants' decision-making performance (Satish *et al.* 2012). In their study, 22 participants were exposed to CO_2 at 600, 1000 and 2500ppm in an experimental chamber. At 600ppm, the source of CO_2 was infiltration of outdoor air and occupant' exhaled air. The higher concentrations were achieved by injecting CO_2 from a cylinder. Participants were asked to complete a computerised decision-making test which was used to assess their cognitive functions. Participants were blind to the CO_2 levels in the chamber. The results from the test were analysed on nine decision making performance scales (basic activity, applied activity, task orientation, initiative, information usage, breadth of approach and strategy). The results showed significant reductions in performance with increasing CO_2 concentration. Relative to 600ppm, at 1000ppm and 2500ppm, statistically significant decrements occurred in six and seven of the nine assessment scales respectively. The most dramatic differences were observed for taking initiative and thinking strategically, where participants' score declined from an "average" rating in 600 and 1000ppm to a "dysfunctional" rating in 2500ppm. Clearly levels of CO_2 below the recommended exposure limits can have significant effects on industry through workers performance.

2.2.8 Summary on CO_2 in indoor spaces

From these studies, it can be concluded that even moderately elevated concentrations of CO_2 can produce physiological symptoms. They also call into question standards that specify minimum ventilation rates in buildings and the workplace exposure limit which is recommended by Health and Safety and Building Regulations organisations. The elevated CO_2 concentration levels that occur in buildings may be a result of failure to supply the recommended outdoor air flow but current specified minimum ventilation rates allows concentrations above 1000ppm. Carpenter and Poitrast (1990) believe that the workplace exposure limit given for CO_2 concentration ignores irritant levels and allows some measure of physiological changes to take place, assuming no permanent adverse effect has occurred. However, the above studies have also shown that there is an association between CO_2 levels and occupant health and productivity. The knock on effect is an economic cost for businesses through increased sick leave and absenteeism and a negative impact on learning and academic achievement for students.

The effects of exposure to CO_2 concentration from background to elevated levels are summarised in Table 2-3 and Table 2-4 presents a summary of symptoms and CO_2 concentrations levels reported in previous studies. In Table 2-3 the concentrations and symptoms presented in red have been recorded in classrooms and offices (Bakó-Biró *et al.* 2012; Seppänen *et al.* 1999).

Table 2-3: Summary of symptoms due to exposure to increasing indoor CO_2 concentrations in indoor spaces

Concentration	**Symptoms**
350 - 400 ppm	Normal background concentration in outdoor ambient air
350 – 1000 ppm	Concentrations typical of occupied spaces with good air exchange
1000 – 2000 ppm	Compliant of drowsiness and poor air
2000 – 5000 ppm	Complaints of headaches, sleepiness and stagnant/stale/stuffy air. Poor concentration, loss of attention. Increased heart rate and slight nausea may also be present
5000 ppm	Workplace exposure limit (8-hour time weighted average)
> 40,000 ppm	Exposure may lead to serious oxygen deprivation, resulting in permanent brain damage, coma and death.

Table 2-4: Studies of the effects of exposure to increasing levels of CO_2 concentration

Study	CO_2 level (ppm)	Symptoms (including SBS)	Performance	Coma/Death	Details/Comments
Dunford *et al.* (2009)	25,000-40,000ppm			✓	Accident
Baxter *et al.* (1989)	>100,000ppm	✓		✓	Eruption of volcanic lake
NIOSH (1976)	> 15000ppm	✓			Controlled experiments to investigate effect of acute intermittent and chronic exposures to CO_2. Gas administered to participants through gas masks
Carpenter & Poitrast (1990)	> 500ppm	✓			Field study – measurements and questionnaires Up to 70% complaints of symptoms at 1500ppm
Norbäck *et al.* (1995)	Ave: 1020ppm	✓			Measurement in bedrooms and living rooms. Significant association between CO_2 and chest tightness
Myhrvold *et al.* (1996)	601 - 3827ppm	✓	✓		Significant association between symptoms and increments in CO_2 levels
Simoni *et al.* (2010)	> 1000ppm	✓			Environmental measurements and questionnaires in schools.
Apte *et al.* (2000)	Up to 798ppm	✓			Analysed data collected from 100 office buildings (environmental measurements and questionnaires)

Study	**CO_2 level (ppm)**	**Symptoms (including SBS)**	**Performance**	**Coma/Death**	**Details/Comments**
Kajtar *et al.* (2003)	600, 1500, 3000, 4000 ppm		✓		Experiments with controlled conditions. Significant difference in spelling performance between 600 and 3000ppm and between 600 and 4000ppm
Satish *et al.* (2012)	600,1000, 2500		✓		Experiments with controlled conditions – significant reduction in performance with increasing CO_2
Tsai *et al.* (2012)	> 800ppm	✓			Field study in an office building – environmental variables measured in August and November. Questionnaires used to record symptoms

2.3 Occupant window opening behaviour

Thermal adaptation is a dynamic process and in buildings, the controls available to occupants will also be affected by factors such as building design and the surrounding environment (e.g. noise and security). In naturally ventilated buildings, the common means of controlling the indoor environment is by openable windows (Raja *et al.* 1998). The appropriate use of windows can be a quick and sometimes efficient way to refresh and cool the air in a room and so acts as a thermal control device in buildings, having an impact on occupant comfort. In temperate climates such as that experienced in the United Kingdom, manual control of ventilation by window opening can result in heat loss from the building during the heating season. Occupant window use behaviour has therefore been studied with the aim of determining and understanding the factors that influence the behaviour and its implication for building energy use.

Another reason for the increasing interest in window use behaviour is the role it plays in maintaining occupant comfort in their indoor environment. In a survey on user satisfaction, having the right temperature and air freshness were revealed to be the most important things about a building (Nicol *et al.* 2012). Because of the energy implication of occupant window use behaviour, there has to be a balance between achieving an environment in which occupants are satisfied and the energy input, particularly the heat input, in buildings. This is most applicable to naturally ventilated buildings where occupants have sole control and play an active role in adapting their environments using windows.

Research on occupant window use behaviour have been conducted in both residential (e.g. Dick & Thomas 1951; Brundrett 1977; Andersen 2009) and non-residential buildings (e.g. Warren & Parkins 1984; Nicol 2001; Haldi & Robinson 2009), using different study methods, in different locations and over different lengths of time.

2.3.1 Methods of study

Window use behaviour has been researched through surveys and three main methods have been adopted for the data collection process: photographic method (Warren & Parkins 1984; Inkarojrit & Paliaga 2004; Zhang & Barrett 2012), continuous indoor environmental measurements (Dick & Thomas 1951; Fritsch & Kohler 1990; Yun & Steemers 2008; Hellwig *et al.* 2008; Herkel *et al.* 2008; Haldi & Robinson 2009; Andersen 2009; Dutton 2009; Wei *et al.* 2013) and questionnaire and observation surveys (Nicol 2001; Johnson & Long 2005; Rijal *et al.* 2007; Liu *et al.* 2012). The choice of a survey type will depend on factors such as sample type and size, location, cost and time available for the study and also the variables being measured and assessed. All methods have their strengths and limitations and researchers have often used a combination to improve the reliability of the results. The common trend in results from these studies is that indoor and outdoor temperatures are the main driving factor influencing window use. However, some studies and the results obtained are limited by the variables measured for example, in a photographic survey, only outdoor conditions are measured and analysed.

2.3.1.1 Photographic surveys

Photographic surveys were conducted by Warren and Parkins (1984), Inkarojrit and Paliaga (2004) and Zhang and Barrett (2012). In a photographic survey, building façades are photographed at specified times to identify windows that are open. This method works best for façades where a clear contrast can be seen between transparencies and glazed sections of window opened and closed states. The technique is not intrusive as building occupants and their spaces are not involved. Also, occupants do not know that they are being studied which could otherwise influence their behaviour. This method is relatively low-cost as it does not require the purchase and installation of expensive data loggers. This means that, where it is possible, whole buildings can be observed, translating to a large sample size of windows. Since only still images of the façades are obtained, there is a lack of information on real time adaptive action. Due to the lack of indoor environmental data, only the influence of outdoor environmental variables can be assessed. Another limitation to this study is occupancy rate and patterns are unknown. The office may not be occupied during observation. Particularly in buildings where night time ventilation is possible, occupants can set the window state to opened and be out of the office for some amount of time during the survey period. The researcher has no way of knowing if the office is occupied or vacant. Visual obstructions and glare can also affect the survey as it may get difficult to identify window states.

2.3.1.2 Indoor environmental surveys

Indoor surveys have been conducted in different types of spaces: bedrooms and living rooms (Dick & Thomas 1951; Andersen 2009), single person offices (Yun & Steemers 2008; Haldi & Robinson 2009; Wei *et al.* 2013), multiple occupancy offices (Yun & Steemers 2008; Haldi & Robinson 2009; Yun *et al.* 2012) and classrooms (Hellwig *et al.* 2008; Dutton 2009). Indoor environmental surveys use environmental data loggers to record indoor environmental conditions and state loggers to record window states. Data can be collected for long periods of time depending on the type of instrumentation used since the equipment can be installed and left in place. Also depending on the quality of the instrumentation, this method can be very efficient as it is not left to the occupants to self-report on their window use actions as is the case of in the questionnaire survey. The state logger records the exact time a window is opened and closed and some can also record the opening width or angle of the window for more detailed information. Recording the time of the action allows for changing state frequency to be analysed if conditions just before and after the action is known. Data with a smaller resolution or time step is required for this and using data loggers can make this possible as they can record at very small sampling frequencies (from one second to several hours intervals). Large data sets can be obtained from small sample sizes. Occupancy sensors can be included to record occupancy patterns, further improving the data set achieved. Due to the cost implication of purchasing the equipment, the sample size for studies using his method may be small. Like the photographic surveys, it is often combined with questionnaire surveys to collect subjective data from occupants.

2.3.1.3 Questionnaire and observation surveys

Questionnaire and observation surveys have also been used in the past by a number of researchers (Raja *et al.* 2001; Nicol 2001; Rijal & Tuohy 2008; Liu *et al.* 2012). Questionnaires are often used in field studies to investigate occupant assessment of their environment and comfort, particularly their thermal comfort. In window opening studies a record of the window state is made at the time the questionnaire is being completed and sometimes spot measurements are taken of the environmental conditions using data loggers. When this is done, an accurate time check is required to be able to link responses and states of building controls with environmental data if measured. Questionnaires allow the occupant to record information about themselves and their reasons for their actions. These are pieces of information that will be missed when only data loggers are used or in a photographic survey. The questionnaires are often used to record personal information perceived environment and perceived and exercised control. Standards such as BS EN ISO 7730 and traditional thermal descriptive scales such as the ASHRAE or Bedford scales are often used to record occupant personal information and perceived environment and comfort details.

When using questionnaires, it is important to inform the participants about the details of the study. Depending on the information requested, confidentiality and ethics approval will be required to ensure that respondents’ answers will not be passed on without appropriate consent. It is also important that both the investigator and the respondent understand the questions and the answers provided in the same way. To ensure this, it is useful to test out the questionnaires in a pilot study where feedback can be given on the questions and the answers can be discussed. Problems with reliability can occur, particularly when participants are asked to take part in repeated questionnaire surveys. Interviews can be conducted in person where open ended questions can be asked and both the interviewer and respondent can explain exactly what they mean in more detail. This can however be time consuming for the researcher and respondent during the interviewing process and for the researcher during the analysis process. This method can also have an effect on occupant responses and behaviour. Respondents may give responses that are socially acceptable or desirable.

2.3.2 Window opening behaviour in schools

Previous research in indoor environments in schools has reported that ventilation is usually poor in classrooms and associations have been found between ventilation rates in classrooms and student's performance (Mendell & Heath 2005; Bakó-Biró *et al.* 2012). Dutton (2009) also identified that there is poor representation of the impact of classroom occupant behaviour in building simulation tools. Studies on window use behaviour in classrooms have been carried out to investigate its influence on the indoor environment and also to improve the prediction of school and classroom building performance. Table 2-5 presents a summary of the studies of window opening in schools. Only two studies have investigated the use of windows in schools and so further work may be needed to extend the study of window opening behaviour in schools.

Table 2-5: Studies of window opening in schools

Study	Location	Sample size	Method	Findings
Hellwig *et al.* (2008)	Germany	8 classrooms in 2 schools	Indoor survey and questionnaires	Total open windows significantly correlated with indoor temperature but not outdoor temperature
Dutton (2009)	UK	2 classrooms in 1 school	Indoor survey	Window opening in the unheated period was significantly influenced by outdoor temperature and solar radiation and the proportion of variation was increased when CO_2 was added, although not significant.

Using environmental data loggers, Hellwig *et al*. (2008) monitored indoor temperature and carbon dioxide concentration in some classrooms in two German schools. In one of the schools the frequency of window opening was also recorded using state loggers. The objectives of their study included to determine if window opening behaviour in schools depended on indoor or outdoor temperature and to analyse the indoor environment in classrooms in terms of thermal conditions and indoor air quality. Outdoor weather conditions were obtained from a weather station located less than one kilometre away from the schools. Only data for the times the classrooms were occupied was included in their analysis. From their indoor environmental data, over 75% of the indoor temperatures were within the comfort limits of 22°C – 27°C during the winter season but the indoor temperature exceeded 26°C for up to 86% of the time in the summer season. However, in the summer and winter seasons a maximum of 3% and 68% of the measured CO_2 concentration was above the recommended 1500ppm respectively. To analyse the association between window opening and temperature, Spearman's rank correlation coefficients were calculated. For all the classrooms considered, a weak to moderate but significant correlation was found between total open window ratio and indoor temperature ($r = 0.15 - 0.43$, $p < 0.00005$). A weak but significant correlation between outdoor temperature and window opening was only found for one classroom ($r = 0.10$, $p = 0.003$) with the remaining correlations not significant. Some explanations provided for these results were the lack of night and early morning ventilation and the lack of or inefficiency of shading devices. The windows were closed after the last lesson and they stayed closed until the beginning of the first lesson. The teachers reported that on arrival they felt the temperature to be the same as after the last lesson on the previous day. Due to the high percentage of glazed area and insufficient sun shading, the temperatures in the classrooms were often very high during the summer. The shading devices often constricted ventilation into the classrooms. Correlations between CO_2 concentration and window opening behaviour was not analysed in this study.

Based on findings that suggested that low ventilation rates has adverse impacts on student work performance and a report showing that some schools experienced ventilation rates below 3 L/s per person resulting in average CO_2 levels above the recommended 1000ppm, Dutton (2009) conducted a post occupancy study in a naturally ventilated school in the UK. For this study, two classrooms were monitored where indoor and outdoor environmental conditions, occupant behaviour and building energy use were recorded for over a one year period. The indoor environmental conditions monitored included air temperature, relative humidity, CO_2 concentration and occupancy through registration. A weather station located on the roof of the building provided information on the outdoor environment. Considering only periods preceding a window opening or closing action, they used logistic regression analysis to determine the dominant contributing environmental factors that influenced window use. The candidate predictor variables were assessed both individually and collectively to produce regression models for window use behaviour which were split into the heated and unheated seasons.

For the unheated period, the analysis showed outdoor temperature and window transmitted solar radiation were the significant predictors of window opening. During the heated periods, none of the environmental factors had a statically significant influence on the probability of window opening. During the study period, CO_2 concentrations measured were over 1000ppm for 10%, 4.7% and 45.7% of the occupied times in March, June and October respectively. For the unheated periods, the outdoor temperature and solar radiation model was extended by the addition of CO_2 concentration. Even though the Cox and Snell's correlation for window opening was increased from 0.14 to 0.21, CO_2 was not a statistically significant predictor ($p = 0.293$).

From his observation and analysis Dutton also found occupants to be within the bounds of common measures of thermal comfort for the majority of window changing events. During the unheated periods, windows were most often opened in the mornings for ventilation and also to prevent anticipated overheating later in the day. He suggested that using the adaptive principle to presume that discomfort influences window use is not valid and found models that are triggered by a discomfort threshold to significantly under-predict occupant window use for buildings that are able to maintain satisfactory thermal comfort levels.

2.3.3 Window opening behaviour in homes

The study of window opening behaviour have usually been conducted to investigate the provision of adequate fresh air from a health and comfort perspective (Fabi *et al.* 2012). This could be because of the variation in ages (from babies through to the elderly), furnishing and activities that can be found in a home (e.g. washing, drying and cooking). As discussed earlier, occupants, furnishing and activities are all sources of indoor air pollution and there are concerns about their impact on occupant health and comfort, particularly in air tight homes (Bone *et al.* 2010).

Table 2-6 presents a summary of the studies of window opening in homes. Most of the studies have been conducted through observations and the results show that there is a variation in window opening due to building and occupant characteristics as well as environmental factors.

Table 2-6: Studies of window opening in homes

Study	**Location**	**Sample size**	**Method**	**Findings: window opening is influenced by**
Dick & Thomas (1951)	UK	20 unoccupied and 8 occupied houses	Observations	Outdoor temperature and wind speed
Brundrett (1977)	UK	123 houses	Observations	Season, weather, room type, family size and whether or there was a stay home housewife
Dubrul (1988)	Belgium, Germany, Switzerland, The Netherlands, UK	Up to 3000 houses	Photographic, indoor survey and questionnaires	Environmental (outdoor temperature and solar radiation) and non-environmental factors (e.g. house type, room type)
Johnson & Long (2005)	USA	1100 houses	Observations	Environmental and non-environmental factors (building characteristics)
Andersen *et al.* (2009)	Denmark	1569 houses	Questionnaire	Outdoor temperature
Andersen *et al.*(2013)	Denmark	15 houses	Indoor survey	Indoor temperature solar radiation and CO_2

Study	**Location**	**Sample size**	**Method**	**Findings: window opening is influenced by**
Schweiker *et al.*(2012)	Japan and Switzerland	3 apartments in Switzerland and 1 dormitory building in Japan	Indoor survey	Indoor and outdoor temperature influenced window opening

Earlier studies to investigation of air change rates and window opening behaviour were conducted by Dick and Thomas (1951), Brundrett (1977) and Dubrul (1988) in houses. Dick and Thomas (1951) made daily observations of window states, recording 147 observations from 15 houses for 26 weeks during the heating season. From their measurements, they observed large variations in window opening habits from house to house and from day to day but observed an underlying relationship between window use and the external climate. The number of opened windows was positively correlated with outdoor temperature and negatively correlated wind speed with 70% of the variation in number of windows opened attributed to outdoor temperature and 10% attributed to wind speed. Brundrett (1977) also studied window opening habits of families in 123 houses. Observations of opened windows were made each weekday for one year and during this period each householder was invited to give their views on window opening. Their observations showed a strong seasonal pattern with windows use, with windows progressively closing with the approach of the colder season and reopening with the approach of the warmer season. Results from multiple correlation analysis showed that mean monthly weather data (temperature, wind speed, humidity and cloud cover) explained between 64% and 68% of the variation in number of opened windows. These observations were based on average weekly weather data. They also observed that the type of room and characteristics of the household were factors influencing window use behaviour. The bedrooms were the most common places for open windows and the kitchens were less sensitive to variation in the weather. Households with a stay at home housewife were more likely to have opened windows and larger families were more likely to have opened windows compared to smaller families.

A study by the International Energy Agency, Annex VIII, involving five European countries used a combination of photographic surveys, continuous indoor surveys and questionnaires/interviews and self-observation surveys to determine what actions occupants used to ventilate their homes and the factors in influencing these actions (Dubrul 1988). To improve the reliability of questionnaire and self-observation surveys, researchers observed the façades of a number of buildings to either take note of the number of opened windows or photograph the façade to identify the opened windows. Both environmental and non-environmental influences on occupant behaviour regarding window use were reported. The factors influencing window use were structured into five categories: dwelling fabric type, life style, control strategies, socio-economic factors and weather factors. Maximum window opening was observed in the morning, decreasing during the afternoon and then another peak observed at about 5pm which was attributed to working inhabitants returning home from work. Results from this investigation backed the results presented by Brundrett that opened windows were most commonly found in the bedrooms.

Similar to Dick and Thomas (1951) and Brundrett (1977), Dubrul (1988) reported a strong correlation between window opening and external temperature. For a temperature range of -10°C to +25°C, a direct linear correlation was found between window use and outdoor temperature (r = 0.96). Other weather conditions that were correlated with window opening were wind velocity, levels of precipitation (rainfall and snow) and sunshine. Window opening was highest at low wind speeds and with increasing precipitation levels. At wind speeds of about 8m/s, nearly all windows were closed. The investigations showed that windows were opened more often for longer periods in sunny weather.

Unlike Brundrett (1977), no clear relationship was found between size of family and window use behaviour. The behaviour of elderly people was found to be significantly different from that of younger people as they observed that the older people were, the less they ventilated. From the questionnaires and the interviews, inhabitants' reasons for windows use were recorded and analysed. In most case inhabitants reported that they opened windows in order to get fresh, remove smells and remove stale air or condensation. Other reasons given included to save energy, maintain a preferred temperature, prevent draughts and reduce outside noise or pollution. Dubrul (1988) concluded that individuals present a great variety of ventilation control patterns as they have their own preferred approach to regulating their comfort.

Johnson and Long (2005) conducted a visual survey on window use in residences in North Carolina, USA to determine factors associated with open windows and doors. The study consisted on 72 two hour long surveys where technicians visited residences to record number of opened windows and doors, weather conditions, occupancy and building characteristics. In general, their results suggested that window opening is affected by factors including occupancy pattern and density, season, wind speed, the number of windows, presence of window screens and presence and operation of air conditioning units. Factors that had no significant effect on open windows opening included time of day and day of the week, air quality forecast and precipitation (recorded at the time of visit).

With the aim of providing more accurate information about driving factors related to window use behaviour, a field study was conducted in Danish residences to investigate occupants' interactions with building controls with special focus on control of indoor air quality as well as thermal comfort (Andersen *et al.* 2009; Andersen *et al.* 2009; Andersen 2009; Andersen *et al.* 2013). In a questionnaire survey, questionnaires were sent out by email, post or phone to Danish dwellings first in September and again in February (Andersen *et al.* 2009). Residents were asked to provide information on themselves and all other occupants (age and gender), on the present state of the dwelling (for example floor area, ownership status, state of windows and shading devices) and on their perceived indoor environment and behaviour during the previous two weeks. Meteorological data was obtained from 25 weather stations across the country and the post code of the respondent was used to identify the closest weather station. Logistic regression methods were used to analysis the potential links between the environmental and non-environmental factors and building control mechanisms which included window open and closed states. As expected and consistent with previous studies, outdoor temperature had a significant impact on window opening ($p < 0.0001$). Other variables that significantly influenced the proportion of houses with window opening were low solar radiation, gender and occupant's perceived environment (IAQ, illumination and noise). Respondent's perception of their environment at the time of response was recorded on a visual analogue scale. Wind speed and thermal sensation did not have significant influence window opening. The result for wind speed is inconsistent with previous studies which have found a decrease in window opening with increasing wind speeds.

Following the questionnaire survey, Andersen *et al.* identified a gap in the driving factors and occupant behaviour due to undesired feedback between occupant's behaviour and the indoor environment. In an attempt to fill this gap, measurements of indoor environment, weather and window opening behaviour were carried out in 15 Danish dwellings for eight months (Andersen *et al.* 2009; Andersen *et al.* 2013). In this study, one living room and one sleeping room in each of the selected dwelling were equipped with data logging devices to record indoor environmental variables and window states. One other objective of this study was to define standardised occupant behaviour patterns which would be suitable for simulation purposes.

Using logistic regression analysis, relationships were derived between environmental variables and window states. As expected, indoor temperature and solar radiation were positively correlated with the probability of window opening and wind speed was negatively correlated with window opening. They also found that CO_2 concentration was positively correlated with window opening. This was because CO_2 concentration before an opening event was higher than when the window remained closed. Also based on the findings on this study, Andersen *et al.* (2013) reported that in the bedroom, CO_2 concentration was the most important variable for the probability of window opening, while it did not have a significant effect in the living room. Indoor relative humidity was also found to influence the probability of both window opening and closing even though it was in the measured humidity was in the range of 30 – 70% (where humans are modestly sensitive to humidity). Since relative humidity affects thermal comfort and perceived air quality, they suggest that it may be the reason for its impact on window use. They concluded that indoor CO_2 concentration and outdoor temperature were observed to be the two single most important variables in determining the probability of window opening and closing respectively.

Other results from this study suggested that not only environmental factors influence behaviour (Andersen 2009). During visits to the selected dwellings, occupants reported that they opened their windows at the same time every day, regardless of environmental factors. The respondents stated that they had been advised to air their dwellings several times a day to avoid problems with house dust mites and mould growth. The driver for this behaviour is therefore a concern over health impacts and not thermal discomfort or perceived air quality. As a consequence, the idea of discomfort being the driver for occupant behaviour may not be right in some cases. However, this may differ between domestic and non-domestic buildings.

The indoor environment and actions on windows were monitored in two separate surveys conducted in naturally ventilated residential buildings in Neuchâtel, Switzerland and a student dormitory in Tokyo, Japan (Schweiker *et al.* 2012). The aim of this study was to identify the specificities of occupant behaviour with regards to window use and to develop and verify occupant behaviour models for application to residential buildings. In Switzerland, measurements were taken in the living rooms for periods covering the summer, winter and a transitional season and in Japan measurements were taken in the summer and winter seasons. The environmental variables recorded were indoor air temperature, outdoor temperature, outdoor humidity, wind speed, rainfall and atmospheric pressure. The window state and opening angle were also recorded using data loggers. Similar to other studies, occupants were asked to complete questionnaires recording information about their typical behaviour and occupancy patterns. As expected, indoor and outdoor temperature had significant influences on window opening. These were included in the model developed to predict window opening. In addition to these, other explanatory variables which were selected for the model based on their statistical relevance were occupant's gender, climatic origin (hot and humid, hot and dry, moderate, cold), geographic background (Europe, Central of East Asia, South America), floor level of apartment/room (ground, middle, top) and orientation of window (east, south, west/north). For both locations, outdoor temperature was found to be the most influential variable on opened windows.

2.3.4 Window opening behaviour in office buildings

Initial window opening behaviour studies were focussed on the energy implication of occupant behaviour on energy performance (Warren & Parkins 1984; Fritsch & Kohler 1990). Results from window opening behaviour studies are therefore aimed at improving the simulation of building energy performance. As discussed in Section 2.2.4.1 and 2.2.4.2, indoor environmental conditions can have an impact on occupants in offices. This makes it necessary to extend the focus of these studies to include the need to achieve adequate indoor air quality and comfortable conditions.

Table 2-7 presents a summary of the studies of window opening in office buildings. It is clear that most of the studies have been conducted in offices and all three methods described in Section 2.3.1 have been used. The offices observed have been in both commercial and academic buildings. Indoor and outdoor temperatures are the most common variables that have been reported as influencing window opening. The only study that reported on CO_2 concentration was conducted in multiple occupancy offices in an academic building where the CO_2 concentrations measured during the survey period were below 1000ppm.

Table 2-7: Studies of window opening in offices

Study	**Location**	**Sample size**	**Method**	**Findings: window opening is influenced by:**
Warren & Parkins (1984)	UK	5 office buildings	Photographic survey	Outdoor temperature, wind speed and solar radiation
Fritsch & Kohler (1990)	Switzerland	4 offices	Indoor survey	Outdoor temperature
Inkarojrit & Paliaga (2004)	USA	1 office building	Photographic and indoor surveys	Indoor (operative) temperature
Rijal *et al.* (2007)	UK	15 office buildings	Questionnaires and observations	Indoor and outdoor temperatures, season, time of day and occupant type
Rijal et al. (2008)	Pakistan	33 office buildings	Questionnaires and observations	Indoor and outdoor temperature.
Yun & Steemers (2008)	UK	6 offices in 2 buildings	Indoor survey	Time of day and indoor temperature
(Herkel *et al.* 2008)	Germany	21 offices in 1 building	Indoor survey	Outdoor temperature
Haldi & Robinson (2008)	Switzerland	8 office buildings	Questionnaires	Indoor temperature (outdoor temperature was less convincing)
Haldi & Robinson (2009)	Switzerland	14 offices in 1 building	Indoor survey	Indoor and outdoor temperature, outdoor relative humidity and wind speed
Zhang & Barrett (2012)	UK	1 office building	Photographic survey	Outdoor temperature

Study	**Location**	**Sample size**	**Method**	**Findings: window opening is influenced by:**
Yun *et al.* (2012)	Korea	4 multiple occupancy offices in 1 building	Indoor survey	Seasonal variation in variables influencing windows open: Spring – CO_2, Summer – temperature. In winter no environmental factors were related to window opening
Liu *et al.* (2012)	China	1 building	Questionnaires and observations	Thermal conditions
Wei *et al.* (2013)	UK	1 building	Indoor survey and observations	Proportion of windows left opened at the end of the day was linked with outdoor temperature

Warren and Parkins (1984), Inkarojrit and Paliaga (2004) and Zhang and Barrett (2012) conducted photographic surveys of naturally ventilated office buildings. To investigate the heat loss implication of window opening during the heating season, Warren and Parkins (1984) identified four window states – wide or slightly opened large windows and wide or slightly opened small windows by taking photographs of the buildings façades twice daily. The type of windows allowed for these wide and slightly opened states to be identified and for each observation period, outdoor temperature, wind speed and direction and general weather conditions (sunny/cloudy/rain/etc.) were recorded. The results from this study showed that outdoor temperature accounted for 76% of the observed variance in window opening. This was followed by solar gain and wind speed which accounted for 8% and 4% respectively. To gain some more insight on occupant behaviour, at the end of the observation period, occupants were asked to complete a questionnaire relating to their adaptive behaviour. Fresh air was most frequently given reason for window opening and so it was suggested that slight window openings is to satisfy indoor air quality needs and wide window openings is influenced by temperature. Results from questionnaires administered to the building occupants as part of this study also showed, for the first time, that occupants act on their windows particularly on arrival and at departure.

Inkarojrit and Paliaga (2004) photographed the façades of their selected buildings four times per day for nine working days alongside measuring indoor thermal conditions at multiple selected locations to investigate whether variation in indoor thermal condition could be used to predict the use of windows and examine the role of indoor temperature as a predictor of the percentage of windows open. From their results, they reported strong, positive correlations between operative temperature and percentage of open windows for all façades and they also showed that these correlations are stronger than that observed for outdoor temperature and windows open. They noticed that the maximum percentage of open windows occurred about two hours later than when the maximum indoor temperature was recorded and suggested that occupants open windows in response to thermal discomfort experienced at a previous time.

In Zhang and Barrett's (2012) study, a total of 1620 windows were observed twice daily in one academic year and at the same time hourly outdoor climatic conditions were obtained from a nearby weather station. From their results, they noticed that only 6.2% of windows were actively used by occupants, regardless of the weather conditions. They found outdoor temperature to be strongly correlated with windows open. The variation in windows open and outdoor temperature occurred simultaneously with very little time lag, suggesting that occupants open windows in response to short term fluctuations in outdoor temperature. They observed a periodic repetition of occupant behaviour in corresponding to seasonal changes. As well as outdoor temperature, wind speed and sunshine hours were significantly correlated with windows open. They reported a variation in windows open on different façade orientations possibly due to solar radiation and wind direction. During the survey period, the surveyor visited occupants with fixed working spaces, inviting them to complete questionnaires about their environment. As this took place, the indoor temperature and relative humidity were also recorded. For their analysis, indoor environmental conditions were not included as the variation between the rooms monitored was widely varied and would have resulted in inaccurate results. As the study target was the entire building, they found it impractical to place a measuring device in every room in the building.

A number of window use databases have been produced from a set of field studies conducted in office buildings in six countries - UK, Sweden, France, Portugal, Greece and

Pakistan. Results from these studies were used to propose the first window state probability models. This work was based on the adaptive principle as described by Nicol and Humphreys and so they state that characterising occupant window use behaviour as a response to discomfort implies that the physical environmental variables that cause the discomfort will motivate the use of windows.

In the UK, data was collected from 25 offices, from seven buildings in Oxford and six buildings in Aberdeen, for a period of about 18 months, by using the questionnaire survey in three different ways – transverse, longitudinal and background surveys. The transverse surveys were conducted one day each month where researchers visited each building with measuring equipment and questionnaires. Researchers recorded information on subjective responses to different aspects of the environment (thermal, air movement, relative humidity, light and noise levels) and their interaction with building controls, including windows, at the time of the visit. This survey included a substantial number of the occupants in each building (374 in Oxford and 909 in Aberdeen). A longitudinal survey was conducted for periods up to three months, using a subset of the transverse sample (94 in Oxford and 125 in Aberdeen). Data loggers were installed at the working stations of the selected occupants to record room temperature at 15 minute intervals. These occupants also asked to provide records on their thermal satisfaction and interaction with building controls up to four times per day. Finally in the background study a questionnaire was sent out to all the occupants to collect information about their attitude to and experience. During the survey periods, weather data was obtained from local meteorological stations for both locations. This data has been analysed and presented by Raja, Nicol, & McCartney (1998) ,Raja *et al.* (2001) and Rijal *et al.*, (2007).

In Pakistan, a year round field study was conducted in 33 office buildings, in five cities to investigate the use of building controls (windows, doors and fans) in modifying the indoor environment (Rijal *et al.* 2008). In the transverse survey indoor environmental conditions and outdoor temperature and the state of building controls (window opened/closed, door opened/closed and fan on/off) were recorded monthly for the study duration.

From both the UK and Pakistan observations, the analysis showed a strong correlation between temperature (indoor and outdoor) and windows open. In Pakistan, the proportion of windows open increased with increasing outdoor temperature but decreased in the highest outdoor temperatures. Also, there was a variation in the proportion of controls used according to the city. The general response from the Pakistani office occupants was that building controls are used to improve thermal environment and the air quality. In the UK, other observations they reported were seasonal and daily variations in window use. The recorded proportions of opened windows were lowest in the winter, medium in both autumn and spring and highest in the summer. The recorded proportion of windows open in the summer was almost five times greater than that in the winter. For time of day, the highest proportion of windows open was recorded in the afternoon. They observed two different types of occupants in relation to window use – "active" and "passive" occupants. This classification was based on answers provided to the background survey question "if you have a window, how often do you actually make adjustments?" Active and passive occupants were those who gave the response of "often" and "never" respectively. The highest proportion of opened windows was recorded for the active occupants.

From the UK results, Rijal *et al.* (2007) used logistic regression analysis to develop the 'Humphreys adaptive algorithm' to predict the proportion of window open. The model was based on indoor and outdoor temperature as separate and then as combined predictors. They also produced separate models for the transverse and longitudinal surveys. The regression coefficient for indoor temperature and outdoor temperature was similar in the longitudinal survey but not in the transverse survey. The accuracy of the prediction in the longitudinal survey was higher (r^2 = 0.95) than that for the transverse survey (r^2 = 0.70). To test the robustness of the predictive equations, the longitudinal equation was used to predict proportion of windows opened from the transverse surveys and vice versa. The results showed that the equation of the transverse survey predicted higher proportions for the longitudinal survey and the longitudinal survey predicted lower proportions for the transverse survey. They demonstrated the implementation of window open proportion into the ESP-r building simulation tool using the equation from the longitudinal survey because of the larger sample size and the wider range of data recorded during the survey. The simulation gave similar results of predicted windows open to those obtained from the survey. From this work, Rijal *et al.* suggest that an adaptive algorithm will better represent human control of windows and it will allow a more accurate assessment of human thermal comfort and building energy performance. From the regression curve, 83% of all the data points were within ±2°C of the regression line. A 4°C is suggested as the temperature band between opening and closing windows. This was termed the "dead band" in which occupants are comfortable and there is no motivation to open or close a window.

Using the data collected from the buildings in Europe, UK and Pakistan, Nicol (2001) concluded that in all the surveys, the proportion of windows open tend to increase significantly as outdoor temperature rise above 10°C. The data showed a difference between the locations observed and the type of questionnaire survey used to collect the data. The lowest proportion of opened windows was recorded for the Pakistan offices and a country-specific analysis of the European data showed higher proportions of opened windows in the UK compared to the other countries. This result indicates that there is considerable variation between different climatic locations. From the data collected, probability algorithms were developed relating occupant behaviour to outdoor temperature. The reason given for using outdoor temperature and not indoor temperature for the analysis was that outdoor temperature forms part of the input of any simulation whereas indoor temperature is an output.

Haldi and Robinson study (2008) also conducted a longitudinal field survey over a summer season. The aim of this study was to investigate occupant's adaptive actions and to identify the reasons and physical conditions for a space to overheat. In the survey participants in the buildings were asked to complete electronic questionnaires, reporting information on clothing and activity level, thermal sensation and preference and adaptive opportunities used, which included opening a window. They found that the general probability of occupants' environmental control actions was better described by indoor temperature rather than outdoor temperature. For window use, there was a clear significant influence of indoor temperature on window opening but a less convincing link with outdoor temperature. Since only opening windows, amongst the use of other controls, were studied, they were not able to reject outdoor temperature as a valid parameter influencing window use.

In a separate questionnaire survey conducted in Chongquig, China, Liu *et al*. (2012) demonstrated that occupants are active players in environmental control and that their adaptive responses are driven mainly by ambient thermal stimuli. In their study that covered all seasons in a year, a total of 148 occupants participated. On survey days, researchers visited the participants twice in the day with the questionnaires alongside measurement equipment to record indoor environmental variables (air and mean radiant temperature, air velocity and humidity). For their analysis, the adaptive responses often used by occupants were put into three categories – technological (operation of building controls), personal and psychological adaptation. From the measured data, they observed slight discrepancies in thermal environmental conditions between the north and the south sides of the building. The results from the questionnaires showed a difference in window use depending on the façade orientation. Due to the difference in thermal conditions on the two sides, they concluded that occupants' use of windows was related to the thermal environmental conditions. The two main reasons given for opening a window were for cooling (52.4%) and for fresh air (47.6%). Other observations made were occupants' adaptive responses in the spring and autumn seasons. Occupants were more likely to maintain thermal comfort by using personal (adjusting clothing) and psychological adaption (thermal expectation and perceived environmental control) rather than technical adaptation. They suggested that the pooled effect of personal and psychological adaptation demonstrates that occupants accept thermal conditions which are not regarded as thermally neutral and so the dissatisfaction rate can be lower than that predicted. Lastly they also observed that a proportion of windows were opened even when air conditioning units were in operation, resulting in energy waste.

Alongside environmental conditions that influence windows open, two studies have reported the variation in windows open due to window characteristics through continuous indoor surveys.

Fritsch *et al.* (1990) conducted a field study in four offices over a seven month heating period where indoor temperature and window opening angle were recorded every half hour. Weather conditions recorded were outdoor temperature, wind speed and solar radiation incident on the window. A correlation between solar radiation and window opening angle was noted but wind speed was found to be weakly correlated. The recorded indoor temperature was found to be relatively constant during the study period and so no noticeable correlation with window opening angle was observed. Outdoor temperature was found to be the only meaningful variable correlating with window position.

Herkel *et al.* (2008) also conducted a field study where they observed the control of windows in 21 south facing offices over a one year period. In the offices occupied by two or three people, the use of 31 small windows and 34 large windows were monitored. The small windows could be left opened after office working hours for night ventilation and were characterised by open or closed states. The large windows were not fully opened after working hours for security reasons. They could be tilted open like a hopper window or widely open like a casement window. During the survey period the status of the windows were therefore recorded as open or closed for the small windows and wide open, tilted open or closed for the large window. Indoor temperatures were recorded at a one minute interval using temperature sensors and occupancy in and out patterns were recorded using a motion sensor. A meteorological station was installed on the roof of the building to record outdoor temperature and solar radiation.

From the analysis, the correlation between window states and outdoor temperature was highest for all three recorded states (small windows open, large windows tilted and large windows open) and this was significant ($p < 0.001$). This was followed by indoor temperature and solar irradiation incident on the window. The correlations for wind speed and direction, occupancy and hour of day were small compared to those for temperature. These are shown in Table 2-8. There was seasonal variation in the window states with the highest percentage of open windows recorded in the summer and the lowest in the winter. This is in line with the observation made by Rijal *et al.* (2007). In addition to this, although the highest frequency in changing window states was observed in the spring and autumn seasons and they suggested that this could be because of the sharp change from colder conditions to warmer conditions and vice versa. The study also showed that occupancy was an important variable that influenced window use, with times of arrival and departure linked with window opening and closing respectively.

Table 2-8: Pearson's correlation between environmental parameters and three different window states (Herkel *et al.* 2008)

Environmental variables	**Small windows open**	**Large windows tilted**	**Large windows open**
Outdoor temperature	0.81	0.63	0.79
Indoor temperature	0.72	0.62	0.76
Solar irradiation	0.52	0.47	0.50
Wind speed	0.18	0.03	0.17
Wind direction	0.16	0.16	0.16

Based on these results and using logistic regression methods, a preliminary model was developed to simulate occupant window use behaviour and predict window state using outdoor temperature and occupancy as the predictor variables. Occupancy was based on time of day (occupant arrival, present and departing).

In other continuous indoor surveys, the time of day variation has been further investigated and window changing states (as opposed to window state) have also been assessed (Haldi & Robinson, 2009; Yun, Steemers, & Baker, 2008; Yun & Steemers, 2008).

Yun and Steemers (2008) carried out a field study where six individual offices in two buildings were monitored for three months over a summer season. The offices selected for monitoring were one and two person offices. Out of the six offices, five were located in one building which does not employ night ventilation and the last office was located in the second building which employs night ventilation for cooling. Indoor temperature was recorded at ten minute intervals and a state logger was mounted on the window frames to record when a window state changed. Half hour recordings of outdoor temperatures were obtained from a nearby weather station for the duration of the field study. Outdoor temperature recorded at 30 minute intervals were obtained from the weather station. Questionnaires were also used to recorded occupant’s evaluation of their indoor environmental conditions.

From their environmental data, they observed a large variation in indoor temperatures distributions in the offices under same weather conditions according to different orientations and suggested that indoor thermal stimulus has a potential to account for occupant window opening patterns. They also identified that occupant window use behaviour was time dependent as most action on windows occurred on arrival and at departure and, particularly for the offices without night ventilation, window states remained unchanged for a majority of the period after arrival and before departure (intermittent period). Their study also provided evidence that each individual responded differently to the thermal stimulus, resulting in different window use behaviour. Based on the observations, they developed a time dependent occupant behaviour model to analyse the relationship between indoor temperature and window opening. They reported a statistically and substantively significant correlation between window opening, indoor temperature and time of day. On arrival, the higher the indoor temperature, the more frequent the window opening occurrence and this increased considerably for temperatures over 22°C. This trend was less distinctive for the office with night ventilation and this could be because of the strong tendency to leave the window opened on departure from the office to utilise the cool strategy. For the intermittent period, a change in window state was barely recorded for both office types. Once a window state had been set on arrival, it often remained in the same state until departure. On departure, windows in the building without night ventilation were closed for security purpose. From this analysis, Yun and Steemers developed probability models of changing a window from one state to another based on indoor temperature, time of day (arrival, intermittent and departure times) and the previous window state.

Information provided through the questionnaires revealed occupants' perceived control was an important factor in understanding window opening patterns (Yun, Steemers, & Baker, 2008) and the study suggested a link between building façade design and occupant's perceived comfort and control of the environment. They found that the highest degree of thermal satisfaction and perceived control was in an office with user-friendly windows that allowed secure night time ventilation. This finding fits with earlier observations by Bordass *et al*. (1993). They reported that in naturally ventilated buildings where ventilation received low scores in perceived control evaluations, the installed windows were of poor designs. They had conducted a survey to investigate relationships between building design, building management, control systems and energy performance. With increasing perceived control comes actual exercised control, as occupants with high perceived control had the higher frequency of window operation.

Following on from their longitudinal survey conducted over the summer period, (Haldi & Robinson 2008), Haldi and Robinson (2009) reported the findings of their extended indoor survey which was based on almost seven years of continuous measurements in 14 cellular offices. All the offices were south facing with identical windows and the ability for night ventilation and they were equipped with temperature sensors that recorded indoor temperature, infrared sensors that recorded occupancy and state monitors that recorded window states. Outdoor temperature was recorded by a sensor located on the roof of the study building and other weather conditions were obtained from a weather station located 7.7km away from the study building. Their results confirmed that of Yun and Steemers (2008) and Herkel *et al.* (2008) showing that interactions with windows occurred mostly on arrival and at departure.

They examined the influence of the environmental variables measured on window opening and noticed a clear increase in the proportion of window opening with both indoor and outdoor temperature, particularly for indoor temperature greater than 20°C. The maximum proportion of opened windows was recorded for outdoor temperature of around 26°C. They also observed a link between decreased proportions of window opening with increasing outdoor relative humidity and wind speed, particularly for speeds greater than

2m/s. However no variations in window use was observed for wind direction. Based on their results, they developed and compared three different modelling methods for simulating occupant window opening behaviour including indoor and outdoor temperatures, outdoor relative humidity and wind speed as the predictor variables. Using logistic regression, they also developed sub-models to predict window changing events for the arrival, during occupancy and at departure. These models were functions of both thermal and non-thermal environmental conditions.

Recently, Yun *et al.* (2012) conducted a one year field study in four multiple occupancy offices located in a building in Suwon, South Korea. The aim of the study was to investigate the link between indoor and outdoor temperature, carbon dioxide concentration and duration of occupancy and window control patterns. Indoor temperature, relative humidity, CO_2 concentrations and window opened or closed states were recorded using data loggers. Outdoor temperature and humidity were recorded with a data logger installed on the roof of the building. Results from this investigation are in agreement with previous studies as it showed that interaction with windows happened mainly on arrival and there was also a clear seasonal variation in window with the highest proportion of window opening on arrival observed in the summer and the lowest observed in the winter. The data collected showed that CO_2 concentrations in the examined offices were in most cases below 1000ppm which is the recommended upper limit level specified by the Korean regulation. Logistic regression analysis was used to derive links between environmental variable and window use for separate times of the day (start, subsequent and end) and for separate seasons. They demonstrated statistically significant relationships between indoor temperature, CO_2 concentration and current window state and window use. They discussed that in the summer when a window is already opened the subsequent use of the window (i.e. closing) is not influenced by thermal factors but rather by CO_2 concentration. This could simply be because when a window is opened, ventilation rate is increased and CO_2 is decreased. They found large seasonal effects on window use patterns and drivers influencing window use: in spring, they reported that CO_2 concentration was the only factor affecting window opening, in summer window opening was explained by thermal stimuli alone and in winter neither temperature nor CO_2 concentration were related to window opening.

With a focus on identifying factors other than temperature that could influence operation of windows, Wei *et al*. (2013) observed end of day window position in offices located in

Loughborough, UK. For this study, 36 offices were monitored through personal observation at specified times in the day for three seasons (summer, winter and autumn). Indoor and outdoor temperatures were recorded during the survey period. The results demonstrated that proportion of windows left opened was proportional to outdoor temperature. Because of the strong dependency of window operation on outdoor temperature, all other factors of interest were assessed as a function of outdoor temperature. The factors which were found to significantly influence end of day window position were season, floor level, gender and occupant's personal preference. Results for season and gender are in line with results from previous studies (Herkel *et al.* 2008; Andersen *et al.* 2009). Façade orientation was not a significant factor affecting window position, contrary to findings by Zhang and Barrett (2012). Based on the idea of 'active' and 'passive' window users presented by Rijal *et al*. (2007), for personal preference, three categories of occupants were defined depending on their interaction with windows at departure: 'habitual closers', leaver opener' and 'adjuster'. The habitually closed windows were observed to be largely independent of temperature, windows left opened very often had some dependency on temperature and adjusted windows was dependent on thermal conditions as they had a higher correlation with outdoor temperature. The main outcome of this study was that there is significant evidence that non-environmental factors affect end of day window position.

2.3.5 Window opening models

From the studies discussed in Section 2.2.4, probabilistic models to predict window use were generated. These models were based on statistical algorithms that predict the probability of a window being in the open state or the probability of a window changing state given one or more independent variables usually indoor and outdoor temperature and time of day.

The commonly used statistical method as used by Rijal *et al.* (2007), Haldi & Robinson (2009) and Herkel *et al.* (2008) is logistic regression which models the relationship between a dependent variable (in this case window state) and one or more independent variable(s). Multiple logistic regression analysis is applied when there are more than one predictor variable. The probability of a window state or an event is defined by the logit model in logistic regression which is given by equation 2-1. The predicted probabilities of window opening can then be calculated using equation 2-2 which is a rearrangement of equation 2-1.

$$\log\left(\frac{p}{1-p}\right) = a + bx \qquad (2\text{-}1)$$

$$p = \frac{e^{(a+bx)}}{\left(1+e^{(a+bx)}\right)} \tag{2-2}$$

where p is the probability of the event, and x is the independent variable (e.g. indoor and outdoor temperature), a is the intercept and b is the slope associated with the independent variable. The regression coefficients a and b are estimated by regression through maximum likelihood estimation. Commonly used statistical packages such as SPSS and R can be used to calculate the regression coefficients. The calculated coefficients are used to plot the regression curve. Table 2-9 presents the calculated regression coefficients reported in earlier studies, conducted in office only, for indoor and outdoor temperature and Figures 2-3 and 2-4 shows a comparison of the regression curves for indoor temperature and outdoor temperature respectively plotted using the calculated constants. Results used to produce these regression coefficients were from office buildings. All the models have been plotted over a wider temperature range than what was measured in the surveys. This has been done for comparison, showing the shape characteristic of the logistic regression models. The green represents study results from UK studies, the red from other European studies (Germany and Switzerland and Nicol (Europe) are from Sweden, France, Portugal and Greece) and the blue is from the Pakistan study. The continuous line represents the indoor surveys and the broken lines are the questionnaires and observation studies (Zhang and Barrett's was a photographic survey).

Table 2-9: Regression coefficients for windows open models with indoor and outdoor temperatures

Study	Indoor temperature		Outdoor temperature	
	a	b	a	b
Nicol (2001) - UK			-3.73±0.6	0.118±0.004
Nicol (2001) - Europe			-2.65±0.11	0.169±0.009
Nicol (2001) - Pakistan			-2.31±0.16	0.104±0.010
Herkel *et al.* (2008) - small window open			-2.99	0.160
Herkel *et al.* (2008) - large window tilted open			-3.13	0.080
Herkel *et al.* (2008) - large window open			-4.05	0.080
Zhang & Barrett (2012)			-4.01	0.100
Wei *et al.* (2013)*			-4.09	0.155
Haldi & Robinson (2008)	-5.64±0.38	0.220±0.015	-1.12±0.15	0.049±0.006
Haldi & Robinson (2009)	-6.22±0.026	0.230±0.0011	-2.47±0.0045	0.121±0.00027
Rijal *et al.* (2007) - longitudinal survey (each building)	-9.61	0.374	-4.34	0.190
Rijal *et al.* (2007) – longitudinal survey (all buildings)	-8.53	0.354	-2.76	0.181
Rijal *et al.* (2007) – transverse survey (each building)	-11.73	0.436	-3.80	0.160
Rijal *et al.* (2007) – transverse survey (all building)	-10.36	0.425	-2.92	0.157
Rijal *et al.* (2008)- Pakistan	-5.33	0.176		
Yun & Steemers (2008)† – without night ventilation	-4.849	0.218		
Yun & Steemers (2008)† - with night ventilation	-39.62	1.823		

* end of day window position only

† probability of changing window state from closed to open on arrival

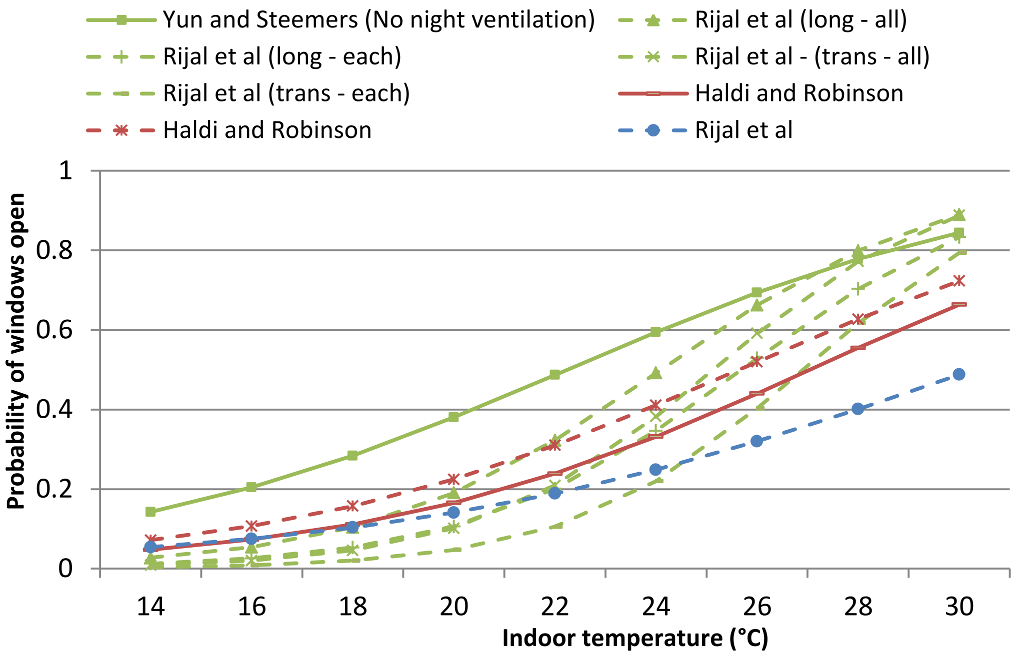


Figure 2-3: Probability of windows open due to indoor temperature, comparison of data from previous studies

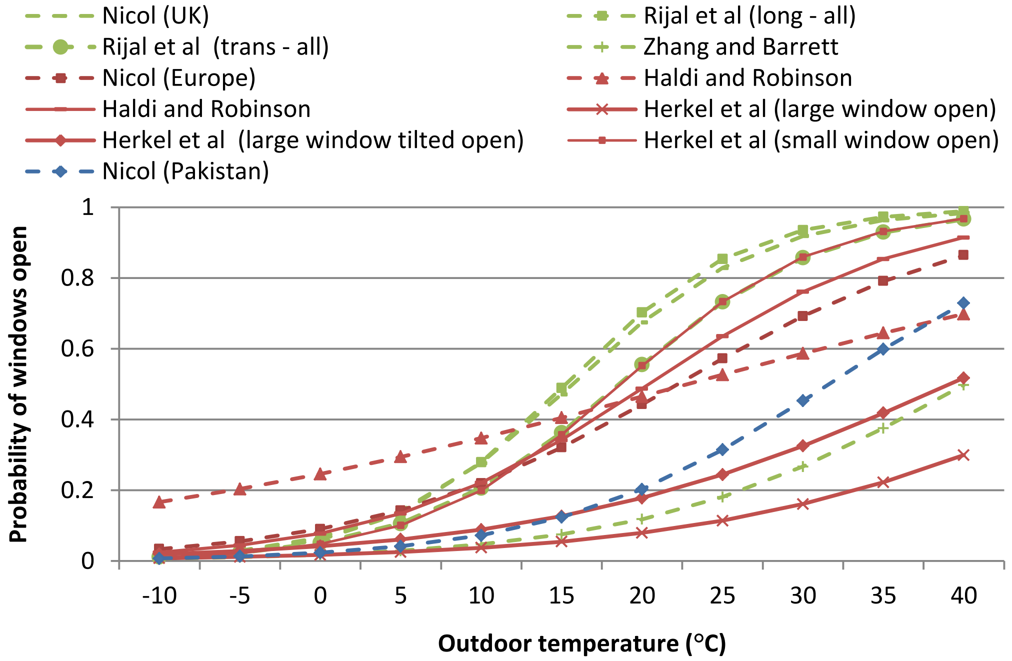


Figure 2-4: Probability of windows open due to outdoor temperature, comparison of data from previous studies

In general, for both indoor and outdoor temperatures, the probability of windows open increases with increasing temperature. For indoor temperature, the predicted probability increases at a higher rate from approximately 18°C. The result from the office with night ventilation shows a sharper increase from 18°C and reaches the maximum at approximately 26°C. The reason could be that occupants may tend to leave their windows opened over night at higher indoor temperatures. Apart from studies by Yun and Steemers (2008), whether night ventilation was possible or not was not mentioned in the other studies. For outdoor temperature, the predicted probability increases as temperature rises from 10°C. This trend is similar in all the results from all of the studies.

However, the curves also show that there is some variation in the results from the previous studies. For instance at an indoor temperature of 20°C, the maximum and minimum predicted probabilities of windows opened are 0.22 and 0.047 respectively. At an outdoor temperature of 20°C, the maximum and minimum results from the predicted probabilities are 0.70 and 0.079 respectively. While all studies show that the probabilities of windows open increases with increasing temperature, there are large variations in the predictions with no agreement regarding the amount of window open at any given temperature, particularly at higher temperatures. This shows that temperature alone is not be enough to predict window use and other variables will have to be taken into consideration.

Figure 2-5 presents the curves produced from the results of studies conducted in the UK only. Rijal's data was a subset of data collected by Nicol for offices in Aberdeen and Oxford and Zhang and Barrett's data was taken from an office building in Sheffield. The longitudinal and transverse surveys produced similar predictions of window open in Rijal's study. However, due to outdoor temperature alone, there is a clear difference in window use in different locations within the same country. Figure 2-6 presents the curves for three different types of windows observed in Herkel's study. Again, there is a clear variation in window use for different types of windows and different opening properties. In their review, Roetzel *et al.* (2010) said it can be assumed that opening properties predefine the related window opening behaviour. This was based on studies that had showed that air exchange can vary with window type, opening size/angle, shape and placement.

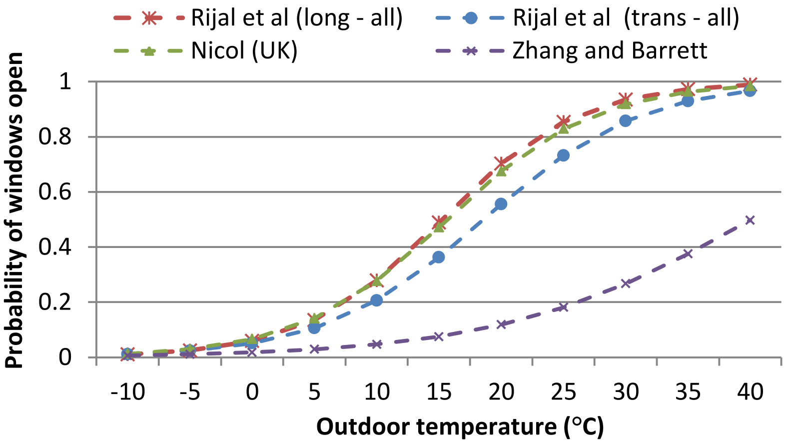


Figure 2-5: Probability of windows open due to outdoor temperature, results from UK studies only

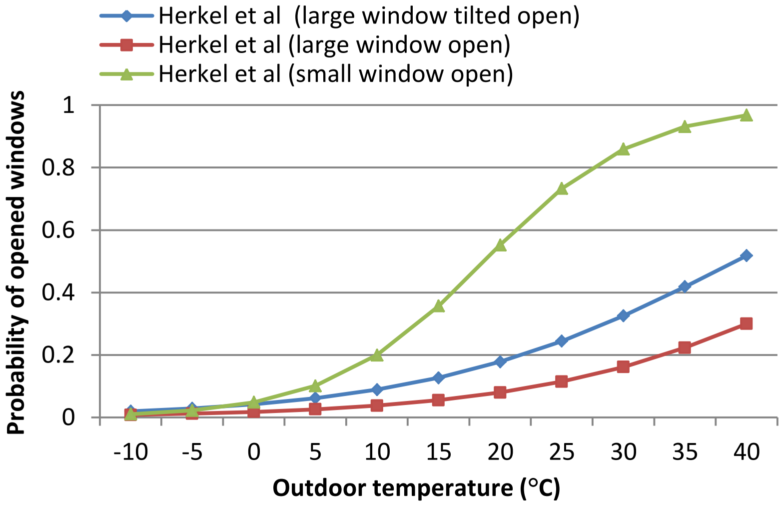


Figure 2-6: Probability of windows open due to outdoor temperature for three different window types, results from Herkel *et al's* (2008) study in a German office building

Rijal *et al's* (2007) window open algorithm (named the Humphreys adaptive algorithm) which was implemented into ESP-r was based on the adaptive theory for thermal comfort (Rijal *et al.* 2007). The inputs were mean outdoor temperature and comfort temperature (calculated from the outdoor temperature). To determine the state of a window, the operative temperature at a defined point is compared to the comfort temperature to decide whether the occupant is likely to be too warm or too cold. If the operative temperature is 2K above or below the comfort temperature then the state is defined as 'hot' or 'cold' respectively. In these cases, the probability of a window being opened is calculated used the logit function derived from their survey data. Using this algorithm, the impact of window opening behaviour on energy use for space heating was analysed. In this analysis two scenarios were compared: one was using the algorithm and the other was without the algorithm where it was assumed that occupants used windows to achieve a ventilation rate of 8l/s/person. The results showed that using the algorithm energy demand was 4% lower than without the algorithm. The Humphreys adaptive algorithm was also used to predict that improvement in building design (implementing a shading device) will further lower the heating demands and improve comfort in the office as fewer windows will be opened.

Even though an algorithm like Humphrey adaptive algorithm is useful in analysing the impact of window opening on comfort and building energy demand, the referenced studies have shown that window opening is not due to indoor and/or outdoor temperatures alone. Other variables such as location of the building, façade design (with or without night ventilation, window size and opening) have an influence on window opening behaviour. The study method, the time of day, other environmental parameters and the type of occupants will need to be taken into account when investigating window opening behaviour.

2.4 Summary

The indoor environment has a significant influence on occupant comfort, health and wellbeing. The main motivation for improving building standards to achieve energy efficiency is to meet legally binding targets for carbon emissions. However, because of the known physiological effects of the indoor environment on occupants, these improvements should not be employed at the expense of internal environmental conditions, particularly indoor air conditions. There is evidence that the current whole building ventilation rate will need to be increased to reduce and prevent sick building syndrome symptoms and respiratory illnesses (Sundell *et al.* 2011). Where infiltration provides useful ventilation to dilute indoor air pollutants, improving airtightness will require appropriate ventilation design to provide adequate air change and indoor air quality.

With the evidence that ventilation is associated with performance of occupants in offices discussed in Section 2.2, there is a real need for understanding occupant behaviour in controlling ventilation to achieve adequate indoor air quality. Several studies have been conducted to investigate occupant window use behaviour in buildings. These have been carried out mainly in naturally ventilated buildings as windows play an important role in achieving and maintaining comfortable environmental conditions. All of these studies have been field observations and measurements which have been different in several ways. They have differed on location of building (different countries, different climates), type of building regarding its use (office, residential and school buildings), observation periods (different seasons, full year, long/short term), type of rooms (bedroom/living rooms, single/multiple occupancy rooms) and façade orientation and design and variables measured. The studies have focussed on investigating different potential environmental and non-environmental drivers that influence window use behaviour and this have been the bases for the variables measured and analysed resulting in different dependencies attained. Nonetheless, some general drivers have been identified as having significant impact on occupant behaviour. The focus on temperature (both indoor and outdoor) as the main driver for window use behaviour makes sense because of its important role in maintaining thermal comfort.

Based on the adaptive principle of thermal comfort and hence using outdoor and comfort temperatures as the main input variables, an adaptive algorithm was developed to determine windows opened and to simulate energy demand for heating. This algorithm was shown to be useful in analysing the benefits of including using occupant window behaviour in simulation. However, a consensus has not been reached on whether indoor or outdoor temperature is the most dominant variable influencing window use. There is also a need to discuss whether using the adaptive principle is appropriate as some studies found that occupants would open windows even when they were exposed to the ‘comfort temperature’, implying that other variables influence window opening.

Earlier studies showed that outdoor temperature was the significant predict for window opening (Fritsch & Kohler 1990; Herkel *et al.* 2008). If this is to be accepted then since outdoor temperature is same in a locality, window use behaviour in buildings in that locality should be very similar regardless of building characteristics (e.g. façade design, orientation) and occupant characteristics and regardless of features close to the building (e.g. presence of trees and busy roads). Yun and Steemers (2008) did not agree with this finding as indoor temperature is affected by parameters such as building characteristics. They therefore found it more reasonable to link window opening to indoor temperature. Andersen *et al* (2012) argue that indoor temperature is affected by the window state and so the predictive variable is affected by the state it is trying to predict, making the analysis of window state based on indoor temperature difficult to interpret. On the contrary to both ideas, Schweiker (2010) had suggested that the best predictor of occupant behaviour should be thermal comfort, the controlled value itself and not indoor or outdoor temperatures. Since thermal comfort is affected by mean radiant temperature, air velocity, relative humidity, clothing insulation and metabolic rate, maybe all these variables will need to be assessed as potential influences on occupant behaviour. According to Borgeson and Brager (2008) even though air temperature has been shown to play a significant role in explaining window use behaviour, our ability to accurately predict window control behaviour is likely to require the modelling of more than one dominant factor. They suggest that it will be better to determine circumstances where the thermal comfort criteria alone inadequately predict observed behaviour.

In office buildings, there is limited understanding in the relationship between indoor air quality and occupant window use behaviour. In the past this has been evaluated through responses provided in a questionnaire and only one study has reported the influence of CO_2 concentration based on results from multiple occupancy offices. In residential buildings, CO_2 concentration was found to influence window opening .Measurements were taken in the bedrooms and living rooms and CO_2 was significant in the bedroom. This room has a different use compared to offices. To be able to better represent occupant behaviour in building simulation, further studies are required which should include non-thermal variables in order to increase the understanding of window use behaviour all types of buildings.

The aim of this PhD project was to identify factors, that influence window opening behaviour and to investigate the relative influence of CO_2 concentration as a driving factor for window opening in thermally comfortable offices.

3 Method

3.1 Introduction

3.2 Case study buildings

3.3 Weather data

3.4 Indoor data

3.5 Statistical methods

3.6 Summary

3.1 Introduction

Methods used to investigate window opening behaviour have been discussed in Section 2.4. The photographic survey and indoor survey with data loggers were used in this study. In addition, an experiment with controlled conditions was designed to investigate occupant window opening behaviour on arrival. This chapter presents a description of the case study buildings used in the photographic and indoor surveys which are described in Chapters 4 and 5 respectively and the data logging equipment used in the indoor survey and the experiment described in Chapter 6.

3.2 Case study buildings

The case study buildings are Jessop West and Arts Tower (hereafter referred to as Building 1 and Building 2 respectively). Both buildings are located in the city of Sheffield. They are part of the University of Sheffield's infrastructure, containing a mixture of office spaces and teaching spaces. Figure 3-1 shows the location and the orientation of the buildings, the location of a local weather station used for this research and the major roads surrounding the buildings. The distance between the buildings is approximately 250m and the local weather station is located approximately 515m west of Building 1 and 280m south-west of Building 2.

In order to investigate occupant window opening behaviour, the case study buildings were selected because they are large, naturally ventilated office buildings, offering a substantial number of openable windows which are accessible for clear observation. In both buildings, occupants have easy access to the windows. Both buildings have design features which are intended to increase occupant comfort and control in the building. For instance, the façade design of Building 1 allows occupants to open windows with minimal noise distraction from the busy surrounding roads. The double-glazed façade installed in the recently refurbished Building 2 reduces air leakage in the colder seasons and heat gains in the warmer season. As efforts are being made for a move towards improving building energy efficiency through improved building standards, the selected buildings provide a good baseline for the observation of occupant window opening where the influence from factors such as poor building standards are minimised. This will increase the relevance of the study findings for future applications.

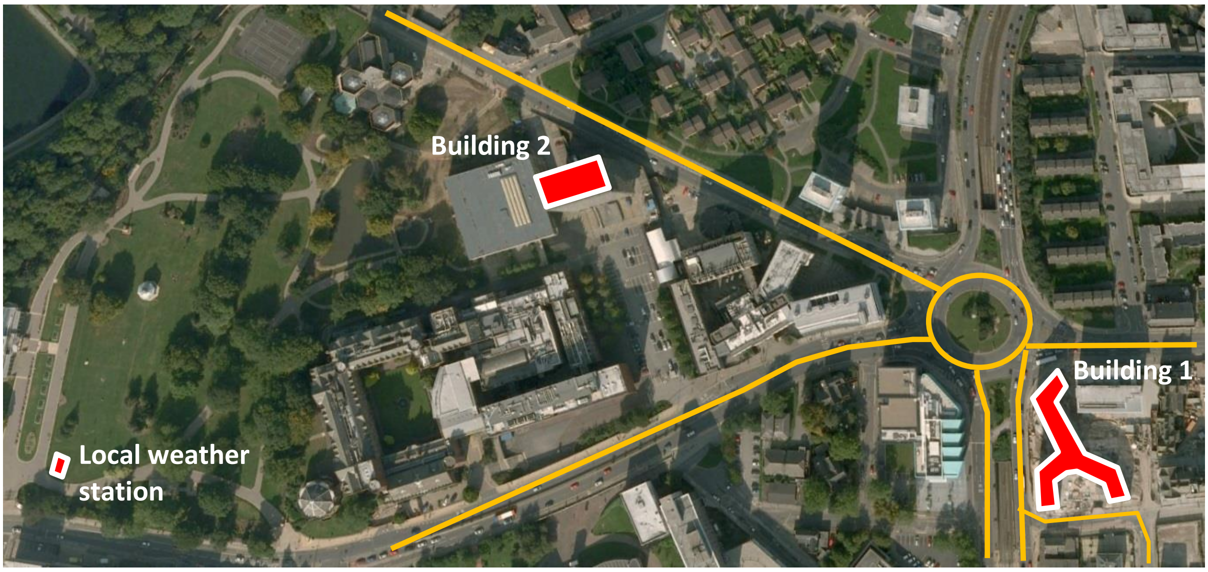


Figure 3-1: Location of the two field study buildings and local weather station (Google Earth, 2013)

The spaces in the case study buildings can be divided into three main groups:

- single person rooms for academic staff
- multiple occupancy rooms, some used as general and research offices and others used for meetings, seminars and teaching
- 'Other' rooms such as restrooms, kitchens, print rooms, etc.

3.2.1 Building 1

The construction of Building 1 was completed in 2008. The roads bordering this building to the north and to the west both exit off the highly trafficked University roundabout (shown in Figure 3-1). A tramline runs between the carriageways of the ring road on the west and stops just south-west of the building. A less busy road runs along the south orientation of the building.

The building is of a heavyweight construction, where the framework has been pared down to a minimum. The concrete columns, soffits of structural elements and the core walls have been left exposed to enable night cooling and temperature regulation. The building is split into three wings, with all wings extending from a central atrium. Each wing is of a different height: Wing 1 has five floors, Wing 2 has four floors and Wing 3 has three floors. All the wings are self-contained, consisting of all the main space types. There are no lecture theatres in this building for large group teaching. Smaller spaces are provided for small group teaching, seminars and meetings. The ground floor contains a café, an exhibition space, a small number of offices and it also acts as a hub for people entering the building. Figure 3-2 shows a typical floor plan of Building 1.

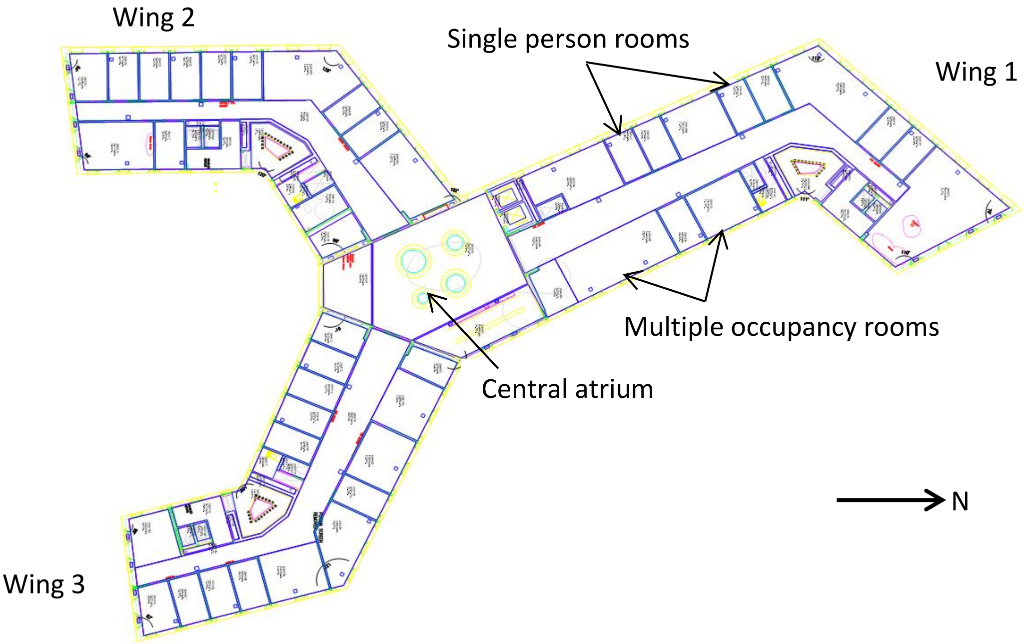


Figure 3-2: Typical floor plan of Building 1 (University of Sheffield Development & Property Services, 2009)

3.2.1.1 Building 1 façade

Building 1 has 16 façades. Due to its proximity to the busy roads on the west and north sides, a double-skin façade system was installed along the west and north-west elevations. A single skin façade was installed along the east and south elevations. The double skin façade was installed in order to reduce noise transfer from the adjacent roads. This system of façade design is defined as a pair of glass “skins” separated by an air cavity (Boake *et al.* 2003). The air space between the glass panels acts as insulation against extreme thermal conditions, wind and sound and venetian blinds can be mounted in the air space for shading. The double skin façade allows natural ventilation as well as acoustic insulation. There are several types of double skin façade designs (Poirazis 2004) and in Building 1 the shaft box façade type is installed. The façade alternates between box windows and vertical shafts. The façade is designed as a breathing skin, with air inlets at each floor level and exhausts from the office to ventilation ducts adjacent to each window. With the shaft box façade, the exhaust ducts extend over several floors, making this type best suited for lower rise buildings. The exhaust ducts maximise the stack pressure developed in the façade, enhancing the effectiveness of the ventilation provided. This window system uses outdoor air to circulate cool and warm air, eliminating the need for mechanical ventilation units. The façade is made of stainless steel and coloured glass. Figure 3-3 shows a section view of a typical shaft box façade and the elevation view of the façade on Building 1. One other advantage of this type of façade is the option for safe night time ventilation, where the rooms are also protected against the elements of the weather, regardless of the window design.

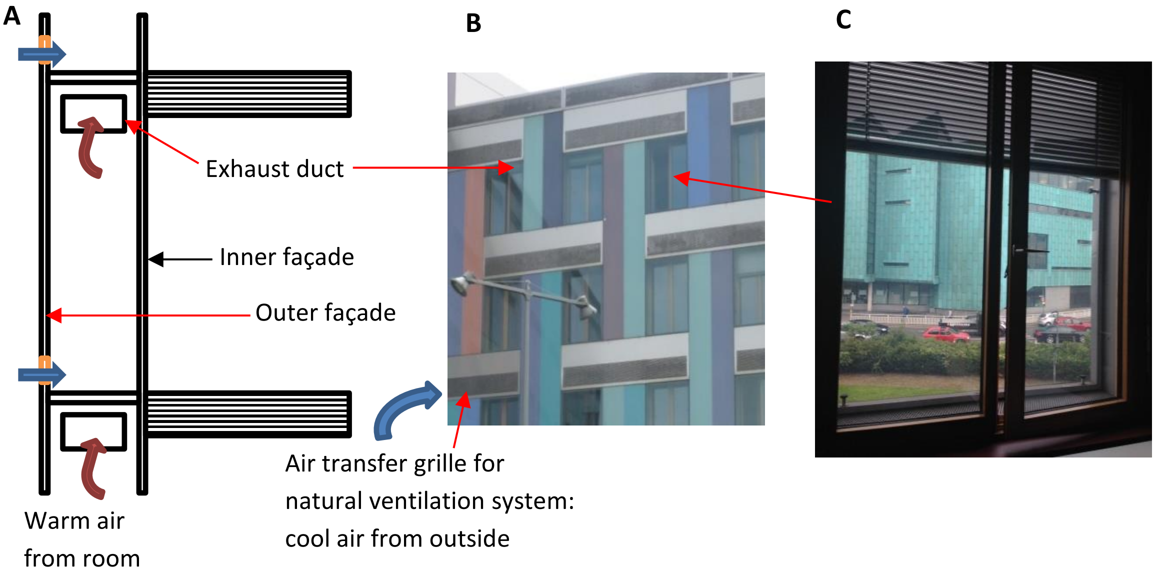


Figure 3-3: Double skin façade of Building 1: (A) Section through double skin façade; (B) Elevation of façade; (C) Window opening from inside the building

3.2.1.2 Building 1 windows

All the rooms have single-sided natural ventilation by openable windows. Venetian blinds are used as shading devices for all the windows. The façade has a repeating geometrical pattern with all windows in a grid system. The windows on the double skin elevation are side hung casement windows which open into the office and the windows on the single skin façade elevation are single turn and tilt windows. These tilt inwards at the top or turn inwards from side hinges for a wider opening. Figure 3-3 shows an open window on the double skin façade and figure 3-4 shows a single skin façade with windows opened in the tilt and turn positions. There are 490 windows in this building.

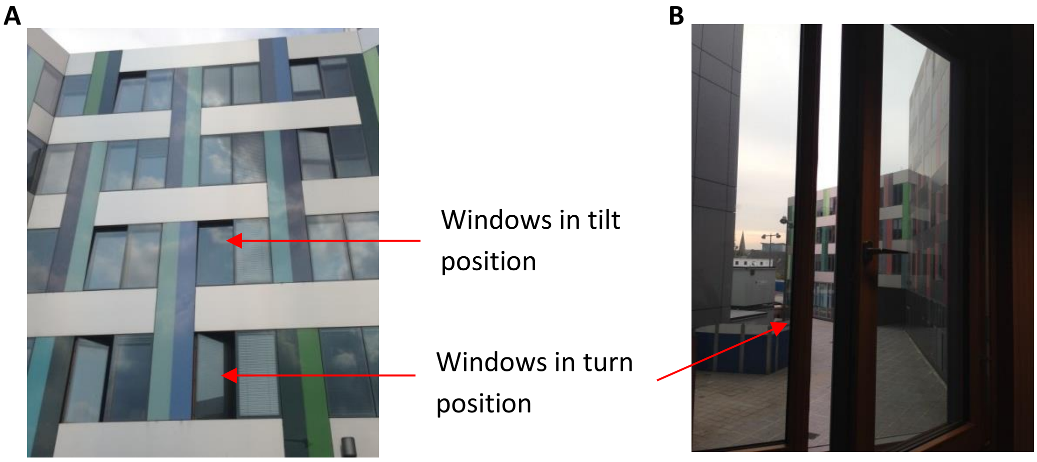


Figure 3-4 : Single skin façade of Building 1: (A) Elevation of façade showing windows open in the turn position and windows in the tilt position; (B) Window opened in the turn position in Building 1

3.2.2 Building 2

Building 2 is a rectangular, high rise building, 78m tall. The long axis of this building is rotated approximately 20° anticlockwise and so the façade orientations are actually 20° east to what they are described as (for example the south façade is 20° east of the south). The building is connected to one of the University's libraries on the west façade by a bridge at the mezzanine level. It was completed in 1965.

The construction of this building is medium weight, with reinforced concrete cores supporting concrete floor slabs which span between the core walls and external concrete columns. The concrete columns form about one fifth of each elevation and these support the building façade which is formed of lightweight panelling (HLM Architects 2007). The building has 20 stories and a mezzanine level above the ground level. There are also two floors below the ground level – the basement and the lower ground levels. The passive zone in this building is from floors 1 to 18. Natural ventilation in these passive zones is mainly due to prevailing wind pressure through openings in the façade. The rooms are centrally heated by perimeter heating coils placed at floor level on the exterior walls under the windows.

In 2009, Building 2 underwent a major refurbishment project. The main purpose of the refurbishment was to extend the life span of the building and improve its environmental performance (HLM Architects 2007). In the refurbishment, the interior space was reorganised and a new façade with double glazing was installed. Thermal modelling performed during feasibility stage demonstrated that the new façade would permit improvements in both winter heat losses and summer heat gains, resulting in a 60% improvement in comfort conditions and will have the potential to reduce carbon emissions (HLM Architects 2007). The refurbishment project was completed in 2011.

The centre, or the core of the building is made up of the lifts and the stairs and rooms are located around the perimeter. The core space is connected to the rooms by a corridor. Figures 3-5 shows a typical floor plan in the Building 2. All the lecture theatres are located in the basement and lower ground levels, along with a café and a resting area for occupants.

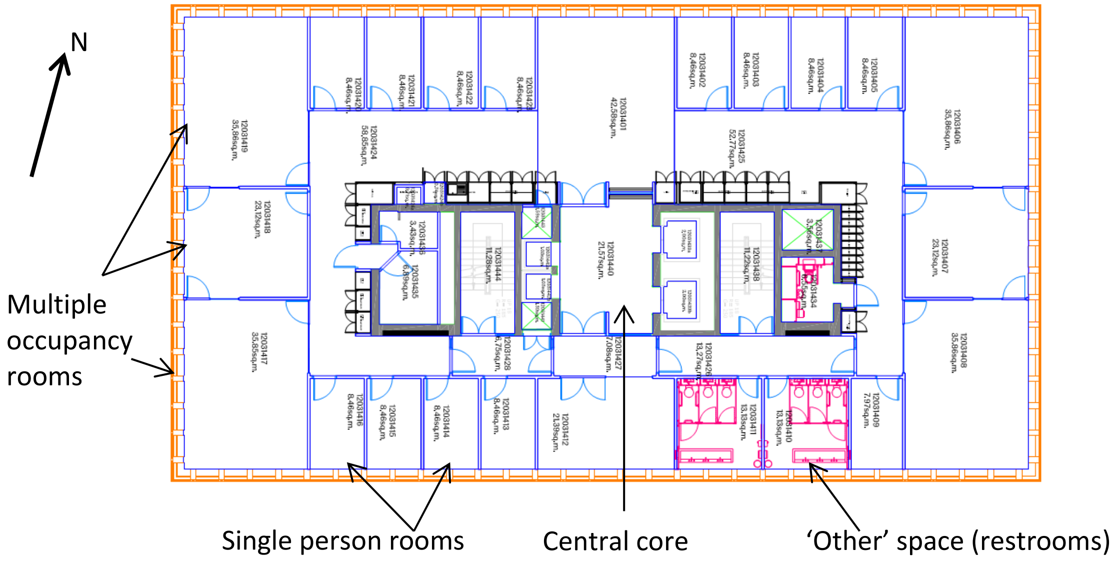


Figure 3-5: Typical floor plan of Building (UoS Estates and Facilities Management, 2007)

3.2.2.1 Building 2 windows

All the windows in the Building 2 are identical and are in a consistent grid design. The windows are double-glazed polyester powder coated aluminium units. They are sash windows located at each bay between the columns. They are rectangular in shape and comprises of a fixed lower panel and an upper panel, with a total height of 2450mm. The upper panel can be adjusted by sliding vertically to satisfy ventilation requirements. The windows on each level are separated by spandrel panels which are approximately 950mm in height. The north and south façades have 29 openable windows in a row (on each level) which are approximately 970mm wide and the east and west façades have 16 openable windows in a row which are 920mm wide each. The corner windows are sealed. There is a total of 1620 windows in this building. Due to the increased weight of the opening panels, the recommended maximum opening dimension for the windows is 200mm. Figure 3-6 shows the window configuration in Building 2.

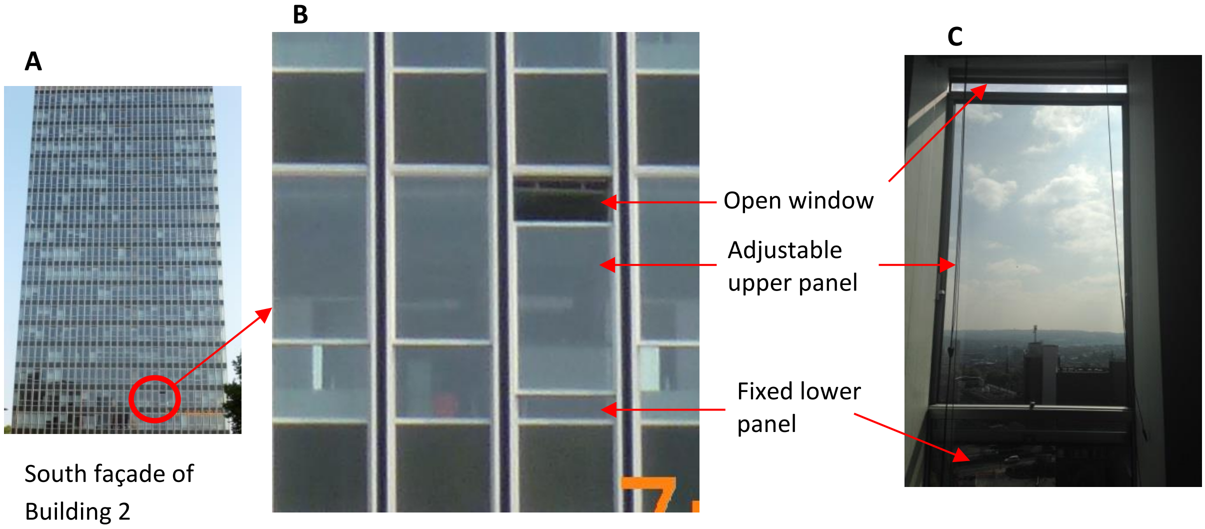


Figure 3-6: Façade of Building 2: (A) Elevation of south façade; (B) Open window as seen from outside and on a photograph; (C) Open window from inside Building 2

3.3 Weather data

Weather data was obtained from a local weather station located at a park close to the buildings (Figure 3-1). The weather station has been recording data since 1882 and it is one of the longest continuously running stations in Great Britain. It was one of the official climatological stations taken on by the Meteorological Office and has been passed into the jurisdiction of Sheffield Museum's Natural Science department (Museum-Sheffield, 2013). Figure 3-7 shows the weather station at the park with Building 2 in view. As mentioned before, Buildings 1 and 2 are approximately 515m and 280m west of this weather station respectively. Previous studies of environmental factors influencing window opening have obtained weather data from personal weather stations located on the roof of the case study building (Herkel et al. 2008; Yun et al. 2012; Dutton & Shao 2010), or from weather stations located a distance ranging from 250m to 7.7km away from the case study building (Zhang & Barrett 2012; Hellwig *et al.* 2008; Yun *et al.* 2008; Haldi & Robinson 2009). Data from the weather station used in the current project is therefore adequate to represent the weather conditions affecting the case study buildings.

Average hourly values of outdoor temperature (°C), wind speed (knots), wind direction, outdoor relative humidity (%), rainfall (mm/hr.) and daily solar hours (hr.) were obtained from this weather station. For outdoor temperature, the minimum and maximum values per hour are recorded. Weather data was obtained for a period from January 2011 to February 2014 whilst the field observations and experiment for this thesis were being conducted.

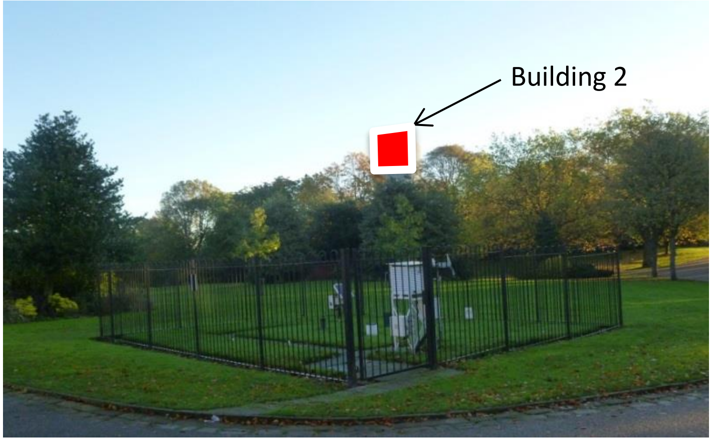


Figure 3-7: Weather station with Building 2 in view

3.4 Indoor data

Data loggers were used to continuously record indoor environmental variables and window and door states. The indoor variables which were recorded were temperature (°C), carbon dioxide concentration (ppm) and relative humidity (%). Software applications were used to read out the data from the loggers onto a computer and converted into an Excel file. In the field work and experiment work conducted for this thesis, two different brands of instruments were used to measure and record indoor air temperature, relative humidity (RH) and CO_2 concentration. One was the HOBO U-12-012 combined with the Telaire 7001 CO_2 sensor (Tempcon, UK) and the other was the Wöhler CDL 210 meter (PCE Instruments, UK). The Wöhler CDL 210 meter is a standalone data logger that records air temperature, RH and CO_2 concentration. The Telaire 7001 instrument is a CO_2 sensor which should be combined with the HOBO instrument to record CO_2 concentration.

3.4.1 Window state equipment

The binary state (open/close) of windows and doors were recorded in real-time using magnetic reed switches which monitor contact closures. A HOBO U9-001 (Tempcon, UK) state sensor which has data logging capabilities was used. This logger and the magnetic reed switch are mounted on the window/door and on the frame to determine when a door or window is opened and closed. The logger checks whether a window or door is closed or open at every second and records the time and state whenever the state changes. A spacing of less than or equal to 6.35mm between the magnet and the logger is considered as ‘closed’ and a spacing of 19.05mm and above is considered as ‘opened’. This HOBO device can record up to 43,000 state changes. The state logger, as shown in Figure 3-8 is small (discreet) in size, with dimensions of 45x60x20mm and it does not cause any distraction or interference with the use of the window.

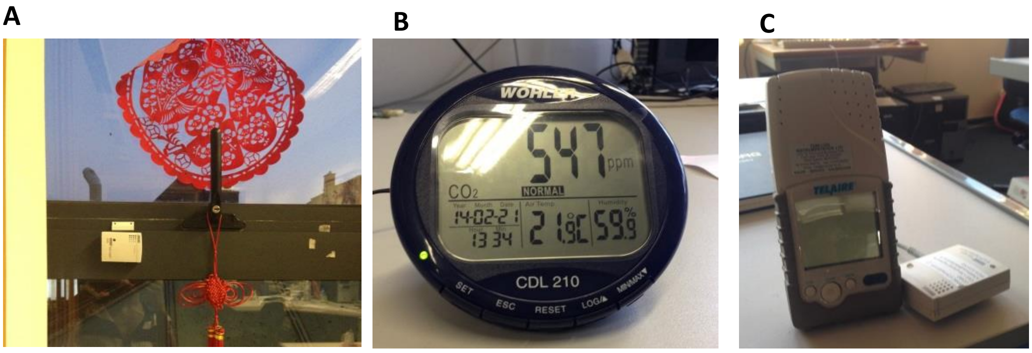


Figure 3-8: State and environmental dataloggers: (A) HOBO U9-001 state logger mounted on a window; (B) Wöhler CDL 210 meter; (C) Telaire 7001 CO$_2$ sensor with HOBO U12-012 data logger

3.4.2 Temperature and relative humidity

Temperature and relative humidity (RH) were measured with the HOBO U12-012 data logger. This data logger is a real-time instrument that uses a thermistor sensor to detect air temperature and a thin-film capacitive sensor to detect relative humidity. The temperature sensor has an accuracy of ±0.35°C from 0°C to 50°C; a resolution of 0.03°C at 25°C; and a range of -20°C to 7°C. The relative humidity sensor has an accuracy of ±2.5% 10% to 90% RH, to a maximum of ±3.5%; a resolution of 0.03% RH; and a range of 5% to 95% RH. The Wöhler CDL 210 meter also measures temperature and RH. The accuracy of the temperature sensor in the Wöhler device is ±0.6°C, a resolution of 0.1°C and can measure a range of -10°C to +60°C.

3.4.3 CO$_2$ measuring equipment

For CO$_2$, the Wöhler CDL 210 CO$_2$ meter measures a range of 0 to 6000ppm, has an accuracy 50ppm or ±5% of the reading and a resolution of ±1ppm. To detect CO$_2$

concentration, the Wöhler CDL 210 meter uses a stable non-dispersive infrared spectrophotometry (NDIR) method. This method is employed for most CO_2 measurements and it is based on the spectrum absorption of light due to CO_2 molecules in the air (Wang et al. 2005). The type of NDIR used the Wöhler instrument is the total absorption spectrometer. According to the manufacturer information, the Wöhler instrument is made up of two infrared sources, a reference cell containing a non-absorbing gas, a sample cell containing the gas of interest and a detector. They work by measuring the intensity of light absorbed by the sample cell. Energy from the infrared sources passes through the reference and the sample cells to the detector. When the sample cell is filled with an inert gas, the sample beam radiation reaching the detector is the same as the beam radiation from the reference cell. However, when the sample cell is filled with gas containing that which is being measured, the radiation is absorbed, reducing the radiation reaching the detector. The difference in the signal between the radiation from the reference and the sample cells is measured by the detector and is related to the amount of the absorbing gas in the detector cell.

The Telaire 7001 CO_2 sensor also has an accuracy of ±5% or ±50ppm of reading up to 5000ppm, a resolution of ±1ppm; and a range of 0-4000ppm. It also uses the dual beam absorption infrared technology method to measure CO_2 concentration as described for the Wöhler instrument.

3.4.4 Physical differences between Wöhler CDL 210 CO_2 meter and Telaire 7001 CO_2 sensor

The Wöhler data logger was selected because of its capability to record and store all three environmental variables required as a standalone equipment. The Telaire 7001 sensor is not a data logger and so it has to be used in combination with a data logger to store the measured CO_2 levels for a later read-out. The HOBO U12-012 device is equipped with an external channel which is compatible with the Telaire 7001 sensor. The Wöhler meter is also relatively cheaper in cost compared to the HOBO/Telaire devices. The Telaire device can display up to 10000ppm of CO_2 reading however a separate connection cable is required for the HOBO device to log readings between 2500 and 4000ppm. The software for reading out data from the HOBO devices are sold separately whereas that for the Wöhler device is included in the purchase of the instrument. This added cost for all the separate components for the HOBO/Telaire instruments make them the more expensive option when compared to the Wöhler instrument. All the devices are lightweight, small and portable and so they do not take up much space when placed on a desk in an office. The

Wöhler meter is more compact with dimensions of 120x100x110mm. The HOBO data logger has dimensions of 58x74x22mm and the Telaire has dimensions of 38.1x165.1x76.2mm. The HOBO device is solely battery operated but the Wöhler and Telaire sensors can be powered externally using an AC/DC adapter.

One limitation of the Wöhler device is the data storage capacity. It can record 5333 measurements of the three environmental variables in series, storing up to 15,999 data points at a sample rate between one second to five hours. The HOBO device can store up to 43,000 data points, sampling at a rate between one second to 18 hours. The Wöhler device has an indicator and audible alarm feature to give a warning when the CO_2 concentration exceeds set limits. Limits can be set for ‘good’, ‘normal’ and ‘poor’ CO_2 levels. For these surveys, this feature was turned off to prevent the alarm from beeping. The display screen of the instrument was also covered with a piece of paper so that occupants would not get distracted by the reading and also to ensure that occupants were behaving as they normally would without the logging instruments in their offices.

3.4.5 Comparing the instruments

To ensure that the instruments could be used interchangeably, the differences in their specifications are discussed here in more detail. Table 3-1 presents a summary of the specifications the Wöhler CDL 210 and the HOBO U12-01/Telaire 7001 CO_2 sensor. The HOBO U12-012 has a higher resolution and accuracy for measuring of temperature and RH compared with the Wöhler CDL 210 meter. The traditional ASHRAE and Bedford thermal comfort scales are descriptive seven-point scales and in studies that use these scales, participants are asked to rate their thermal sensation by selecting a number on the scale. A change in temperature that will change a response on the thermal sensation scale is 3°C for sedentary occupants (CIBSE 2006). Therefore for an accuracy of 0.6°C and a resolution of 0.1°C, the Wöhler meter is still capable of recording changes in temperature measurements that can cause significant difference in occupants’ thermal sensation. The range of temperature measurement in the Wöhler meter is sufficient for use as indoor temperature. The design temperatures for offices is in the range of 20 – 24°C and 23 – 26°C for winter and summer respectively (CEN 2007b). These design values are specified for the Category II of naturally conditioned buildings which is recommended as the ‘normal’ criterion. The description for this category is “normal level of expectation and should be used for new buildings and renovation”. This description best describes the buildings used in this study and so the indoor temperature should be designed to these ranges. This guarantees that the temperature will be within the specified measuring range for the instrument.

For relative humidity, both instruments have the same specified range and this is sufficient to measure the indoor humidity levels. Most humidity sensors have this specified range and the typical accuracies for humidity detectors in data loggers are between 2 and 5%. The acceptable range of humidity in most indoor spaces is between 40% and 70% (CIBSE 2006) and according to this guide, for sedentary, lightly clothed occupants, humidity becomes apparent when temperature increase above 26°C – 28°C. For practical purposes, the influence of humidity on warmth in moderate thermal environments may be ignored. In the majority of thermal comfort surveys, humidity has little effect on thermal comfort and it does not vary much in the whole room and so measurement in a single place is often sufficient (Fanger 1970; Nicol *et al.* 2012). For these reasons the Wöhler meter is sufficient for use in measuring humidity with its specification.

For the CO_2 concentration measurement, there is a difference in the measurement range. Even though the Wohler meter has a smaller range, studies on association of ventilation rates and CO_2 concentrations on occupants in indoor environments have showed that CO_2 concentration in office buildings typically range from 350 – 2500ppm (Seppänen *et al.* 1999). In dwellings, Anderson *et al*. (2013) measured CO_2 concentrations in the range from 328 – 4636ppm and in schools Bako-Biro *et al.* (2012) measured CO_2 the a range from 644 – 5000ppm. Even with the maximum level recorded in classrooms, the Wohler meter will be suitable for use in these environments. All other specifications (accuracy and resolution) for CO_2 measurements are same for both meters.

Table 3-1: Specifications of indoor data logging instruments

Parameter	**Wöhler CDL 210 meter**	**Telaire 7001 and HOBO U12**
CO_2	Method: NDIR (Absorption) Range: 0 – 6000ppm Resolution: ±1ppm Accuracy: 50ppm or ±5% of reading (whichever is greater)	Method: NDIR (Absorption) Range: 0 – 4000ppm (Display range: 0 – 10,000ppm) Resolution: ±1ppm Accuracy: 50ppm or ±5% of reading up to 5000ppm (whichever is greater)
Temperature	Range: -10°C - +60°C Resolution: 0.1°C Accuracy - ±0.6°C	Range: -20°C - +70°C Resolution: 0.03°C Accuracy - ±0.35°C
Relative humidity	Range: -5 – 95% Resolution: 0.1% Accuracy - ±3% (for 10 – 90%), ±5% (for other values)	Range: -5 – 95% Resolution: 0.03% Accuracy - ±2.5% (for 10 – 90%), ±3.5% (for other values)

To further compare the instruments, an experiment was conducted to assess the agreement between the readings. A Wöhler CDL 210 meter was placed next to a Telaire 7001 CO_2 sensor/HOBO U12-012 and the indoor environmental conditions were recorded over a period of 12 hours at one minute intervals. The comparison results are shown in Figures 3-9 and 3-10. The correlation coefficient is highly significant, where $r = 0.972$, $p < 0.001$, $n = 721$, indicating that the measurements from the two loggers are significantly related.

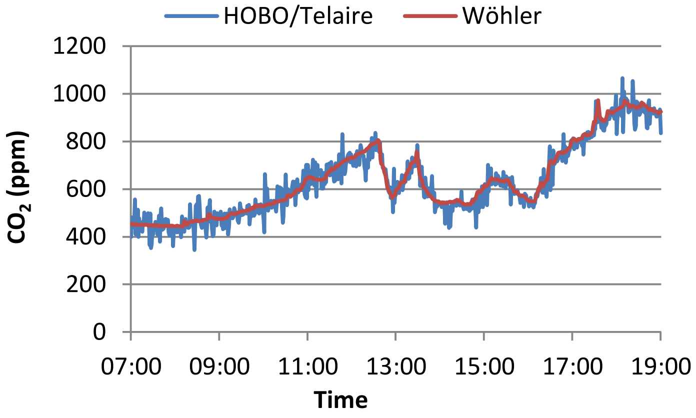


Figure 3-9: Comparing CO_2 measured using Wöhler and Telaire/HOBO instruments

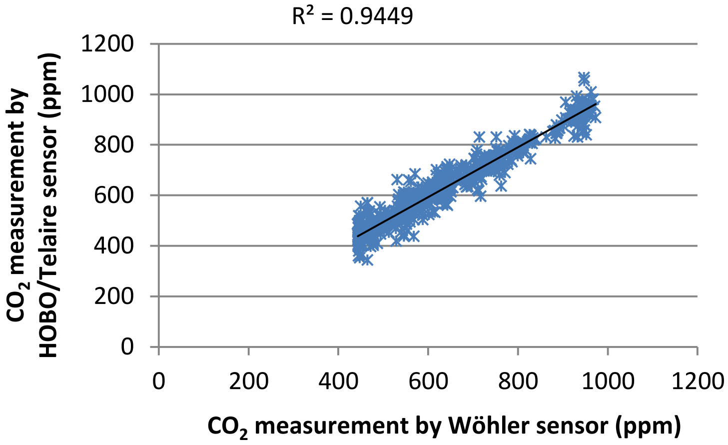


Figure 3-10: Correlation between CO_2 measured using Wöhler and Telaire/HOBO instruments

According to Bland and Altman (1986), using the correlation coefficient alone is not enough to judge whether the data measured agree sufficiently. For instance, the correlation is not affected by a change in scale in the readings but agreement between the readings will be affected. They go on to propose a statistical method which is deemed more appropriate for determining the measure of agreement between the data. This method is a direct comparison of the measurements from the two instruments to determine how far apart their measurements can be and if this difference will be acceptable or not.

Figure 3-11 shows a plot of the difference between the readings against the mean. This plot allows for the relationship between the measurement error and the mean of the readings to be investigated. For the plot, there is no significant relationship between the difference and the mean of the readings. The standard deviation (SD) of the difference is a useful estimate used to investigate whether the difference between the readings are significant or not. When most of the difference lies within $Mean \pm 2SD$, the difference between the readings is acceptable and the two loggers can be used interchangeable.

The results show average discrepancies of 78ppm above the mean and 63ppm below the mean. The mean of the difference was 7.44ppm and the standard deviation was 35.9. Comparing the HOBO/Telaire logger with the Wöhler logger, the former will record readings 78ppm more or 63ppm less than the latter.

Since most of the difference in readings lie within the $Mean\ \pm 2SD$, this is acceptable and the loggers can be used interchangeably. Figures 3-12 and 3-13 show the temperature and RH data recorded by the two instruments and Table 3-2 presents the correlations and results from the agreement analysis for the indoor parameters measured. The values presented are how much more or less the HOBO logger will record when compared with the data recorded by Wöhler logger. For all the variables, the differences in readings are acceptable. It is therefore acceptable to use the Wöhler and the HOBO/Telaire data loggers interchangeably.

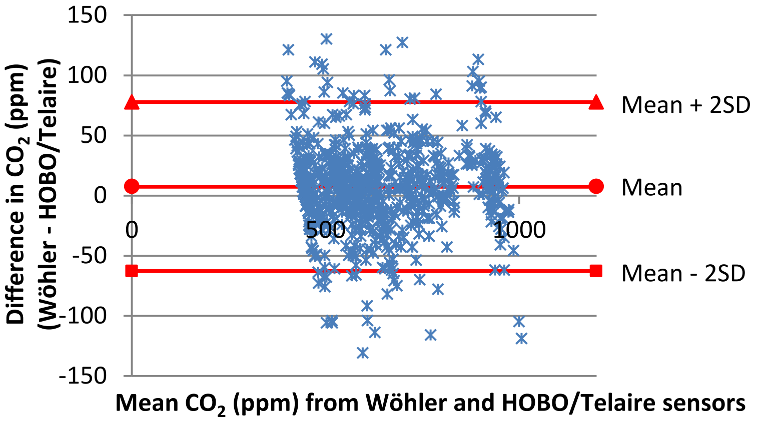


Figure 3-11: Differences against mean for CO_2 measurement

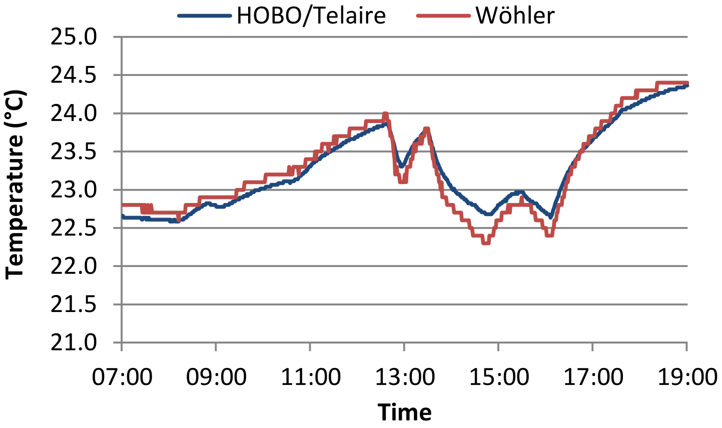


Figure 3-12: Comparing indoor temperature measured using Wöhler and Telaire/HOBO instruments

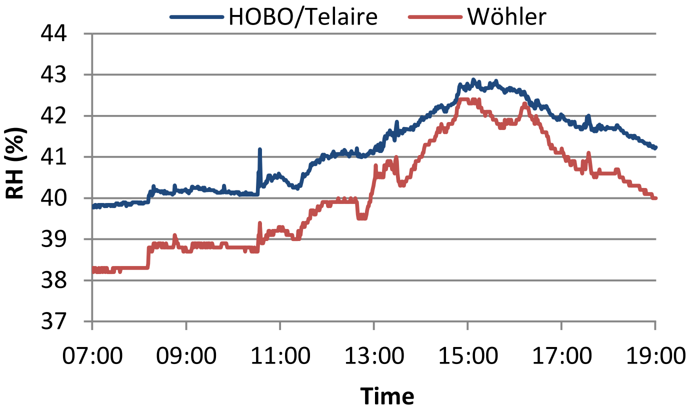


Figure 3-13: Comparing indoor relative humidity measured using Wöhler and Telaire/HOBO instruments

Table 3-2: Correlations and agreement analysis between readings from loggers

Statistic	**CO_2 concentration (ppm)**	**Indoor temperature (°C)**	**RH (%)**
Correlation (r)	0.972	0.968	0.989
Mean of difference	7.44	0.0074	-1.075
Standard deviation (SD)	35.9	0.152	0.357
Mean + 2SD	77.7	0.306	-0.375
Mean – 2SD	-62.8	-0.291	-1.775

3.5 Statistical methods

Statistical tests were employed to analyse the data collected in the field and experimental work. IBM SPSS Statistics Version 21 (IBM 2012) was used for the data analysis. It is an established computer software package used for data management and quantitative statistical analysis. It is capable of handling large amounts of data and can accurately perform a wide variety of analyses using the appropriate statistical functions.

To analyse the data collected from the field study and the experiment, logistic regression and chi square methods were used. These methods were selected based on the type of dependent (outcome) and independent (predictor) variables being investigated. In the current study, there was one dependent variable which was categorical. This was window state – open or closed. The independent variables were either categorical (e.g.

temperature condition – comfortable or high) and continuous (e.g. outdoor temperature, wind speed). The theories of the selected statistical tests are explained in detail in the Sections 3.5.1 and 3.5.2.

3.5.1 Logistic regression test

Logistic regression is used to predict the probability of categorical outcomes from either categorical or continuous predictors. The categorical variables are coded at the different levels for the analysis. In window use studies, the outcome is window state (window closed = 0 or window opened = 1). The continuous predictor variables are the environmental variables (temperature, CO_2 concentration, relative humidity, wind speed) and the categorical variables are occupancy times (arrival = 1, intermittent = 2 and departure = 3). When there are two categorical outcome variables, the analysis is known as binary logistic regression. This statistical method is often used to infer the probability of windows open based on environmental variables (e.g Haldi & Robinson, 2008; Nicol, 2001; Rijal *et al.*, 2007).

The probability of windows open can be based on one or more independent variables. When more than one predictor variable is being assessed, it is known as a multivariate regression analysis and it is expressed by the logit transformation given in equation (3-1). In a linear regression, the assumption is that the relationship between the outcome and the predictor variables is linear. However this is not the case in logistic regression as the outcome is categorical and not linear. Hence the logit transformation describes this non-linear relationship in a linear form. Detailed theoretical background on logistic regression analysis can be found in (Field 2009; Christensen 1997).

$$\log\left(\frac{p}{1-p}\right) = a + b_1X_1 + b_2X_2 + \cdots + b_nX_n \tag{3-1}$$

Where p is the probability of a window opened given the predictor variables with values of X_1, X_2, …, X_n, a is the intercept of the regression equation and b_1, b_2, …, b_n are the regression coefficient of their corresponding predictors. The magnitude and the sign of the regression coefficient indicate the strength and the direction of the relationship. The larger the magnitude, the stronger the relationship between the variables and positive values indicate that as the predictor variable increases, the probability of the response of interest (window opened) increases. The regression coefficients are calculated using the maximum likelihood estimation procedure. This procedure finds values that best indicate how likely the observed outcome can be predicted from the observed values of predictors. The probability p can be obtained from the inverse of the logit transformation using equation (3-2) and the resulting probability curve can be drawn based on the corresponding predictor variable.

$$p = \frac{e^{(a+b_1X_1+b_2X_2+\cdots+b_nX_n)}}{1+e^{(a+b_1X_1+b_2X_2+\cdots+b_nX_n)}} \quad (3\text{-}2)$$

The solution from the logistic regression analysis may be more stable if there are no strong correlations between the predictor variables. Multicollinearity or correlation between the independent variables can result in inflated standard errors and biased regression coefficients, making it impossible to estimate the effect of one variable over the other.

A number of statistical tests are used to evaluate the statistical significance of the predictors and the goodness-of-fit of the model. This is particularly useful when there are more than one predictor variable.

The likelihood ratio test is a good measure of the significance of the predictors. It is used to check the difference between the model without the predictor and the model with the predictor and it is based on the model deviance. The significance of the contribution of a variable can be tested by calculating the difference between the model with only the intercept, known as the null deviance, and the model with the independent variable included, known as the model deviance. The likelihood ratio test is therefore defined as the deviance difference by the inclusion of the independent variable. If the model deviance is significantly smaller than the null deviance, this indicates that the model is a better fit as it best describes the outcome.

Goodness-of-fit is an index of how well a model fits the data from which it has been generated and it is based on how well the data predicted by the model corresponds to the data that has been observed (Field 2009). In logistic regression, the Pseudo R^2 is a statistic used to measure how well a model fits the data. It measures the proportion of explained variance in the model as predictors are added. In other words, it is a measure of how much the model's predicting ability is improved as a result of the inclusion of the predictor variable(s). R^2 can vary between 0 and 1, where 0 indicates that the predictor contributes nothing to the outcome and 1 indicates that the model predicts the outcome perfectly. There are several versions of Pseudo R^2 used in logistic regression: Cox and Snell's and Nagelkerke's R^2. They are based on the null deviance, the model deviance and the sample size. The maximum R^2 calculated by Cox and Snell is not 1 and therefore Nagelkerke's R^2

was suggested to overcome this problem (Field 2009). For the analysis conducted in the current project, the Nagelkerke R^2 will be used.

Where the influence of more than one variable on the outcome is assessed, an information criterion is a useful statistic for variable selection or model comparison. The information criteria are a goodness-of-fit statistic that measures the complexity brought on by the addition of multiple predictor variables. They cannot be intrinsically interpreted but have to be compared to other models with different predictors. The information criteria can be calculated for each variable or for a combination of variables and the model with the lowest criteria indicate that the model is a better fit to the data compared to models with higher values. There are two options of information criteria: Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). For both options, the lower the value the better. For the analysis conducted in the current study, the AIC will be used.

Logistic regression does not rely on any distributional assumptions (normality, linearity or homogeneity). However, the solution may be more stable if there is no strong correlation between the predictor variables and if continuous independent variables have a normal distribution, with no obvious outliers.

In a multivariate regression analysis, it is important that the predictor or independent variables included are not strongly correlated to each other. Strong correlation between two or more of the predictor variables is known as multicollinearity. Multicollinearity makes it difficult to interpret the regression coefficients of the correlated variables (Field 2009). The standard errors of the regression coefficients increase as correlation between the variables increase, making the coefficient less stable and less representative of the sample the data was collected from. As well as this, multicollinearity makes it difficult to examine the individual influence of one predictor over the other when the predictors are correlated. Field suggests that correlations above 0.8 are a sign of multicollinearity. A more detailed method used to detect multicollinearity is to calculate the variance inflation factors (VIF). The VIF gives an indication of whether a predictor variable has a strong correlation with another predictor variable. A VIF value of 10 and greater is seen as a good value at which there is definitely a problem with multicollinearity (O'brien 2007). Lower threshold values of 3 and 5 have been suggested as values at which there might be multicollinearity issues (Menard 1997). Despite multicollinearity, all the predictor variables can be left in the analysis to produce a final model. However, there are a number or remedies that can be applied in an attempt to reduce the effects. One such remedy is to exclude one of the correlated variables from the final model. The risk here is that some information may be lost when a predictor variable is not included in the analysis. Another remedy for dealing with multicollinearity is to collect more data to further assess the correlation between the variables or to establish which variable has the strongest effect on the outcome.

To deal with outliers, Field (2009) suggests several options. Similar to dealing with multicollinearity, the particular data can be removed or changed but doing these can result in loss of information. An alternative option is to transform the data. A log transformation is an appropriate transformation used for correcting skewed data. If the data set includes negative or zero values, a constant is added before the transformation is carried out.

3.5.2 Chi square test

The chi-square test is an appropriate test for analysing data where both the predictor and the outcome are categorical. A chi-square test is suitable for examining the effect of the independent variable on the dependent variable. It enables the frequency of the outcome to be analysed given the predictor. This test will be applicable to the data obtained from experiment with controlled conditions conducted for this thesis. In the experiment, the predictor variables were *comfortable* or *high* temperature and *ambient* or *high* CO_2 concentration and the outcome variable was window opened or not opened. The chi-squared (χ^2) is defined as the standardisation of the deviation of each score and it is expressed by equation (3-3). The analysis presents four categories of data. From the data collected in the experimental work conducted for this thesis, examples of the categories are: windows opened – comfortable temperature, windows opened – high temperature, windows not opened – comfortable temperature and windows not opened – high temperature. Their respective frequencies are the observed frequencies.

$$\chi^2 = \sum \frac{(observed - expected)^2}{expected} \tag{3-3}$$

Where *observed* is observed frequencies in each data category and *expected* is the frequency that is expected due to chance. The chi-squared is used to test the difference between the two frequencies.

The calculated χ^2 value is compared to a critical χ^2 with the corresponding degree of freedom and a selected statistical level (e.g. $p = 0.05$). If the calculated value is equal to or greater than the critical value, the difference between the expected and the observed frequencies is said to be significant. For example, to determine whether the difference between window use in the two temperature conditions (comfortable or high) is significant at a statistical level of 0.05, the calculated χ^2 value should be equal to or greater than the critical χ^2 which is 3.84 (degree of freedom = 1). Critical χ^2 at the corresponding degrees of freedom and significance levels are published in most statistical books (e.g. Field, 2009; Hinton, 2004).

The solution determined by the chi-squared test is best when the expected frequencies for each category are at least five. Below this, the test may fail to find a genuine effect. Also, to be able to apply a chi-squared test, each participant should contribute only one set of information to be included in the analysis (i.e. it cannot be applied to a repeated measures test) (Field 2009; Hinton 2004).

3.6 Summary

In this chapter the selected case study buildings are described in detail, including the façade and the window designs. Features of these buildings are typical of the efforts that are being made to improve energy consumption in buildings while also improving the indoor environment quality for occupancy. Due to the size and the location of the buildings, a significant number of windows are available and accessible to observe for the field surveys conducted for this thesis. The monitoring equipment used in the field survey and the experiment are also described in detail. Since two different data loggers were used in the study, a comparison test was conducted and the results from the statistical analysis showed that the difference between the environmental variable measurements was not significant, indicating that it was acceptable to use the loggers interchangeably. The statistical tests which will be used in analysing the data from the field surveys and the experiment have been presented to explain how they are appropriate for this study.

4 Photographic survey

4.1 Introduction

4.2 Case study buildings

4.3 Survey period

4.4 Data acquisition

4.5 Initial observation

4.6 Univariate analysis

4.7 Multivariate analysis

4.8 Seasonal variation

4.9 Other factors considered

4.10 Window state changing events

4.11 Time-dependent analysis

4.12 Summary

4.1 Introduction

A photographic survey was carried out to investigate the influence of external environmental variables on windows open. The photographic survey method is explained in detail in Section 2.3.1.1. This method used in the current survey is typical of a repeated transverse survey (Nicol *et al.* 2012). In a transverse survey, a whole or a substantial proportion of the population is included in the study. In window opening studies, the population refers to the total number of windows in the buildings. A large sample size reduces sampling bias to ensure that the results are representative of the population. In a repeated transverse survey measurements are taken over short periods of time to avoid sudden or significant changes in variables but the measurements are repeated, for example, once a month, once a season or once a year for a period of time in order to ensure that different sets of similar conditions are investigated.

Features of the current photographic survey that makes it typical of a repeated transverse survey are:

- A significant proportion of windows were observed –in total 2004 windows out of a possible 2110
- Observations were made for two weeks at a time
- Observations were repeated to include three seasons (summer, autumn and winter)

4.2 Case study buildings

The case study buildings are described in more detail in Section 3.2. Both buildings contain a mix of cellular single person offices, large multiple occupancy spaces for a variety of uses such as meetings and teaching and spaces for services. Building 1 has a total of 490 windows and Building 2 has 1620 windows.

4.3 Survey period

In order to investigate a range of environmental conditions on window states, the photographic survey was conducted over a two week period in the summer, autumn and winter seasons. Of the three studies that have used a photographic survey to observe window use behaviour (Warren & Parkins 1984; Inkarojrit & Paliaga 2004; Zhang & Barrett 2012), only the study by Zhang and Barrett was conducted over an extended period of time to include a wide range of environmental conditions. In their study window positions were recorded twice daily for 16 months during the university academic semesters. Warren and Parkins conducted their survey over 13 weeks to obtain 90 sets of observation (45 in the morning and 45 in the afternoon) and Inkarojrit and Paliaga conducted their survey over nine working days where three selected façades were photographed four times each day. In the current survey, 132 sets of observations were obtained, making the survey period comparable with that of Warren and Parkins (1984).

The three seasons selected for observation in this project present a variation in outdoor thermal conditions which should enable a variation in window opening behaviour to be observed. Zhang and Barrett (2012) found that there was very little difference in the number of windows opened in the spring and autumn seasons. This may be because very little difference in the average outdoor temperatures was recorded in the spring and autumn seasons. They found that the peaks in outdoor temperature relating to peaks in number of opened windows occurred simultaneously. For the current project, based on the premise that number of windows opened is significantly influenced by outdoor temperature, spring and autumn outdoor temperatures for 2010, 2011 and 2012 were assessed in order to predict if a significant difference would be found between the numbers of opened windows in these seasons. The average outdoor temperatures for the spring and autumn seasons are presented in Table 4-1. The data was obtained from the weather station described Section 3.3. In each year, higher temperatures were recorded in the autumn months and the average difference between the autumn and the spring temperatures was 1.1°C. For this difference in outdoor temperature, previous studies reported very little change in the proportion of opened windows, particularly at temperatures lower than 10°C as often experienced in the in the spring and autumn seasons (Nicol 2001; Rijal *et al.* 2007; Haldi & Robinson 2008). For example From Nicol's model of use of building controls, the difference in proportion of opened windows corresponding to this difference in mean outdoor temperature is approximately 0.1 (Nicol, 2004). From their 2008 study on window use in Danish dwellings, Andersen *et al.* (2013) suggest that for occupant behaviour models including seasonal effects on window use behaviour, results for the spring and autumn seasons are interchangeable, where a set of results from spring can be used to represent results for autumn. Therefore only three seasons were deemed sufficient for the photographic survey presented in this thesis.

Table 4-1: Average outdoor temperatures for spring and autumn recorded in 2010, 2011 and 2012

Year	Spring	Autumn
2010	8.7	9.6
2011	10.3	12.2
2012	9.0	9.5
Average	9.3	10.4

In the summer and winter seasons, the highest and lowest outdoor temperatures are expected and so these two seasons will offer a good comparison between the thermal conditions that influence window opening behaviour. Since the heating in both of the case study buildings are centrally controlled, window opening in the winter season can have an implication on the building heating energy consumption.

4.4 Data acquisition

A significant proportion of the façades on both buildings are easily accessible making them easy and safe to observe from vantage points in the surrounding areas. For Building 1, 94.7% of the total windows were observed (464 out of 490). These windows were on all façades, from the first floor to the top floor on each wing. The proportion of windows that was not included in the observation was because their view was blocked by other parts of the building. Window opened states on the single-skin façade elevations were easily identifiable as there is a clear contrast between the opened state of windows (in both the tilt and the turn positions) and the remaining glazed part of the façade. The complex nature of the double-skinned façade and the high number of obstructions surrounding the building meant achieving usable images with the camera was problematic. One other limitation of studying windows on the double-skinned façade is that when the venetian blinds are lowered to fully cover the windows and they are in the slat angle position, the window state is not distinguishable. It is however possible to observe the window states from inside the building to record the number of opened windows. It was concluded that a photographic survey for the double-skin façade elevations of Building 1 was not suitable and instead a paper-based survey method was employed. For the double skinned façades, a façade-plan was outlined on paper and opened windows were manually recorded during observation times. This building is a medium rise building with a maximum of six floors. The ground floor was not included in the survey and so windows on a maximum of five floors were observed. There are four sections of the double-skinned façade, two of which have five floors and the remaining two have four floors. This made it easy and quick to record window states manually.

For Building 2, floors 1 to 18 were considered for observation. Part of the view of west façade is obscured by the adjacent building and hence floors one to five on this façade were excluded from the survey. The total number of windows observed was 1540 out of the 1620 (95.1%).

In total across both buildings 2004 windows observed in the survey. The data collected from the photographs and the manual survey were organised into a database. The buildings and all the rooms in each building were assigned a unique identification number. For each room, information such as type of space, floor, room number, façade/orientation were recorded. Similarly all windows were assigned a unique identification number. The windows were linked to the rooms they were located in. A record was created for the window state of each window at each observation time.

4.4.1 Sampling times

In order to determine the most suitable sampling interval and time of sampling, a pilot study was conducted where all the façades of Building 1 was photographed for one week in June. Prior to the study, hourly average outdoor temperatures for June 2010, 2011 and 2012 recorded at the weather station were used to show the daily variation of temperature levels. This was used to select the most appropriate sampling times and intervals which would demonstrate the potential influence of outdoor temperature on the use of windows.

Zhang and Barrett (2012) identified flexible bands and core hours when the building they investigated was occupied. This was between 07:30 and 19:00, where the flexible band was between 07:30 and 09:30 and again between 15:30 and 19:00 and the core hours were from 09:30 to 15:30. Figure 4-1 presents the average hourly outdoor temperature for the month of June in 2010, 2011 and 2012 and the flexible and core hours in a day. The temperature profile shows that the maximum hourly change in temperature occurs between 07:00 and 12:00 and again between 16:00 to 19:00 hours. These times overlap with typical arrival and departure times in an office building. Yun and Steemers (2008) observed that a change of window state mainly occurred on arrival and departure of the occupant and that once a window state had been set up on arrival, it generally stayed the same during the intermittent period until departure. This suggests that it'll be important to observe window states at the typical times which represent arrival and departure.

Based on the observations made by Zhang and Barrett and by Yun and Steemers about times of frequent window use and periods of maximum change in temperatures, the observation times for the current photographic survey were selected. The times were selected in order to capture the potential variation in number of windows open due to variation in outdoor temperature and the time-dependency behaviour of occupants. Table 4-2 presents the sampling times selected for the observation and explains the reasons for selected times, relating to the temperature profile in Figure 4-1.

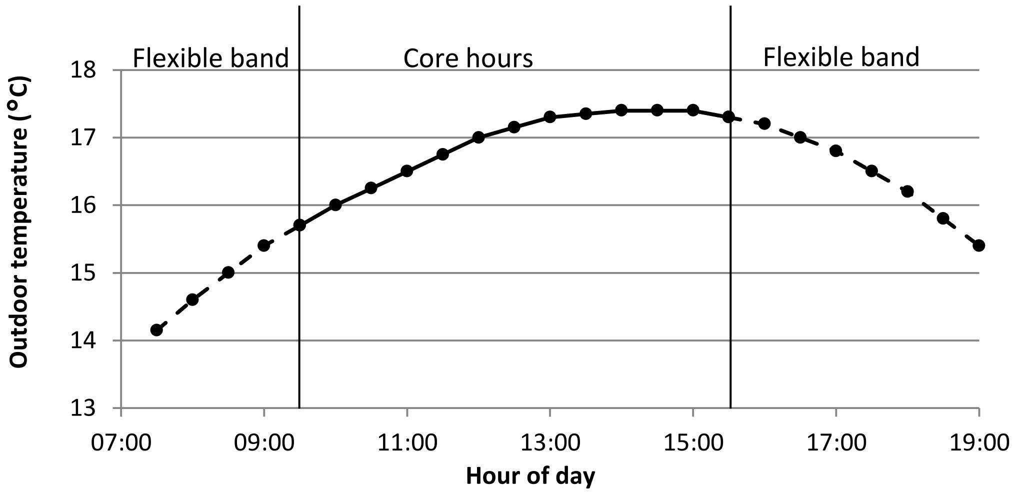


Figure 4-1: Profile of average hourly outdoor temperature in June

Table 4-2: Selected sampling times in pilot survey for surveying windows open/closed status

Time	Description
07:00 – 07:30	To capture window states before typical working hours. The lowest outdoor temperature in the flexible band before the start of the core hours
10:00 – 10:30	To capture windows open within the arrival period. Outdoor temperature at this time is approximately one degree higher than the average temperature in the flexible preceding band
13:00 – 13:30	To capture windows open during occupancy (between arrival and departure). There is a steady increase in outdoor temperature from 07:00 up to this time and the temperature has increased by 2.4°C from the flexible band.
15:30 – 16:00	To capture any change in windows open during occupancy and also due to departure (since this time also represents the end of the core hours period). There is little change in temperature from the previous observation time (approximately 0.01°C).
18:00 – 18:30	To capture window states after the core hours. The temperature at this time is 1.4°C lower than the temperature at the end of the core hours.
19:30 – 20:00	To capture window states at the end of the second flexible band and determine the utilisation of night ventilation.

The results from the pilot study showed a consistent daily pattern, with little difference in the days of the week. On average approximately 73 windows were opened daily, accounting for 15.5% of the total number of windows observed. The maximum proportion of open windows was recorded during the intermittent period – 18.1% and 18.2% were recorded at the 13:30 and 16:00 observation times respectively. The minimum proportions of open windows were recorded at the end of the day, with 13.2% at 18:30 and 10.6% at 20:00.

At the observation times, the proportion of windows that had changed state from the previous observation time was determined and this is presented in Figure 4-2. The window changing states at the 07:30 observation is based on the window states from the last observation on the previous day. There was an increase in windows opened early in the morning particularly on the corridors. This coincided with the time the cleaners were arriving. At the 10:30 observations, 4.5% of windows had changed from closed to open and at the 18:30 observations, 7.1% of the windows had changed from opened to closed. These two figures indicate the operation of windows at the start (assumed on arrival) and end (assumed on departure) of the working day. It can also be seen that at 13:30 and 16:00, there was little difference in the proportions of windows that had changed from closed to opened and from opened to closed as compared to the other observation times. This result is in agreement with Yun and Steemers (2008).

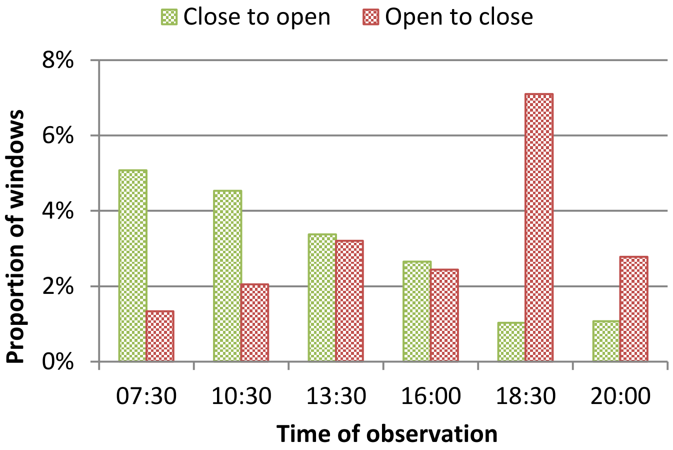


Figure 4-2: Average proportion of windows changing states observed in pilot survey

The sampling interval and times for the survey were selected based on the result of the pilot study. A sampling interval of four times a day was selected in order to demonstrate an approximate daily profile of open windows with regards to changing outdoor temperature. Table 4-3 presents the sampling times at which the façades were photographed. The last observation was carried out between 18:00 and 18:30 in order capture as much as possible the proportion of windows that change state at the end of the working day. This seems to happen after 16:30, with the highest change from opened to closed occurring between then and 18:30. However, from the pilot study, some operation of windows also occurred between 18:00 and 20:00. A later observation time of 18:30 will be sufficient to enable a higher proportion of operation of windows to be recorded. A first observation between 07:00 and 07:30 was selected in order to capture window states possibly before first entry by building users and also in order to determine the proportion of window used in night ventilation, that is, the windows that had remained opened after the last observation on the previous day. The observation between 10:00 and 10:30 would represent window use on arrival. From the pilot study, after the first observation, the highest proportion of windows that had changed from closed to opened was recorded at this time, implying that occupants would open a window when they arrived or within a certain period after arrival. Finally, the intermittent observations were reduced to one as there was only a small difference in operation of windows at these times. These observation times were deemed sufficient to obtain a profile for windows opened which represents occupant behaviour. Observing the window states four times daily for two weeks in three seasons would result in 120 sets of observations and a total of 184,800 window states.

Table 4-3: Sampling times and intervals at which the case study buildings were photographed

Time	Reason
07:00 – 07:30	Window state before start of office work hours
10:00 – 10:30	Change in window state possibly due to first entry or initial change in window state
13:00 - 13:30	Change in window state during intermittent period
18:00 - 18:00	Change in window state possibly due to last departure

4.4.2 Survey procedure

The façades of the buildings were photographed using a digital camera equipped with a high level of angular resolution provided by a sensor with 16.1 effective megapixels. The camera is equipped with an image-stabilised ten times optical zoom lens, with a full frame sensor equivalent focal range of 25mm ultra wide-angle to 250mm telephoto. The level of resolution offered by the high pixel count enables high quality photos to be taken and when viewed on a computer screen, allowed easy and accurate identification of opened windows. When photographing Building 2, the ultra-wide angle lens and optical zoom allowed the entire building façade to be photographed so that it filled the frame and in doing so maximised the resolving capability of the sensor. By using as close to the widest angle of the lens possible, it was also possible to utilise the largest apertures of the lens which meant fast shutter speeds could be used to reduce the potential for blur from camera shake in long exposures. The possibility of blur from camera shake was also reduced by the image stabilisation feature. When photographing the building at night, the camera still provided clear and usable images. Window state was clearly visible in rooms where the lights were on, however, in rooms where the lights were off, it was harder, though not impossible, to discern window state. During the survey periods, weather data was obtained from the weather station described in 3.3.

4.5 Initial observations

From the photographic survey, two observations of window use were considered: the number of windows that were recorded as open at each observation time (proportion of windows open) and the proportion of windows that had changed states from the previous observation time (window changing states - changed from closed to open). The influence of the weather variables recorded during the survey period on the proportion of windows open and window changing states were assessed. Univariate analysis was carried out to determine the influence of individual environmental variables and multivariate analysis was carried out determine the influence of multiple variables on proportions of windows open and window changing state events. Differences in proportion of windows use due to seasons, buildings, façade characteristics and room type were also investigated. The influence of outdoor temperature was used to assess the differences. For window changing state, a time-dependent analysis was carried out to examine the influence of occupancy time periods on window opening.

To analyse the observations, the binomial family of generalised linear model (GLM) was used. The GLM gives the option to use the frequency of the response or dependent variable and the total observations corresponding to each value of the independent variable in a logistic regression analysis. In the current photographic survey, the response variable was the number of open windows and the number of windows that had changed state. The independent variables were the recorded weather data obtained from the weather station.

4.5.1 Windows open

The maximum and minimum proportions of windows recorded open were 50.8% and 1.3% in the summer and winter observation periods respectively. The average proportion of windows open at the times of observation and for each season is presented in Figure 4-3. As expected, the highest proportion of windows open was recorded during the summer monitoring period and the lowest, during the winter monitoring period. There is also a slight variation in time of day with the highest proportions of window open recorded at the times between the first and the last observations times. This is the number of windows which are open and not a change in state. Therefore it seems intuitive that most windows would be open during the occupied hours. This variation was similar in all the seasons surveyed. The descriptive statistics of the recorded weather parameters during each observation period are presented in Table 4-4 and variations in proportion of windows open with weather conditions are shown in Figure 4-4 to Figure 4-11.

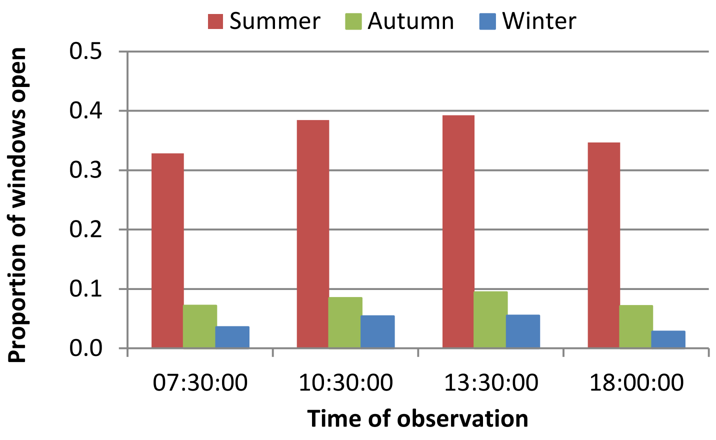


Figure 4-3: Proportion of windows open for Building 1 and Building 2

Table 4-4: Environmental data during survey period

Season		Outdoor temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Rainfall (mm/hr)
Summer	Min	11.7	35	1.0	0.0
	Max	27.3	90	5.1	0.2
	Mean	21.4	58	2.7	0.0
	St Dev	4.2	15	1.1	0.0
Autumn	Min	3.7	61	0.5	0.0
	Max	16.6	97	7.2	8.4
	Mean	9.9	84	3.4	0.3
	St Dev	3.3	9	1.4	1.2
Winter	Min	0.8	69	0.0	0.0
	Max	7.5	96	7.2	1.9
	Mean	4.7	86	4.3	0.3
	St Dev	1.8	7	1.4	0.5

4.5.2 Outdoor temperature

The highest proportion of windows open and the highest outdoor temperatures occurred in the summer and the lowest proportion of windows open and lowest temperatures were recorded during the winter observation period. Figure 4-4 presents the variation in the proportion of windows open with outdoor temperature recorded in all three observation periods. There is a clear increase in proportion of windows open with increasing temperature in the summer. Figure 4-5 shows more clearly the variation in the autumn and winter seasons and the pattern of increase is more noticeable in the autumn compared to the winter.

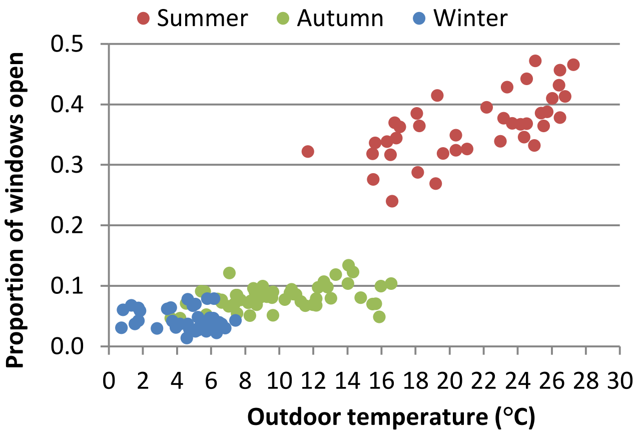


Figure 4-4: Variation of proportion of windows open with outdoor temperature

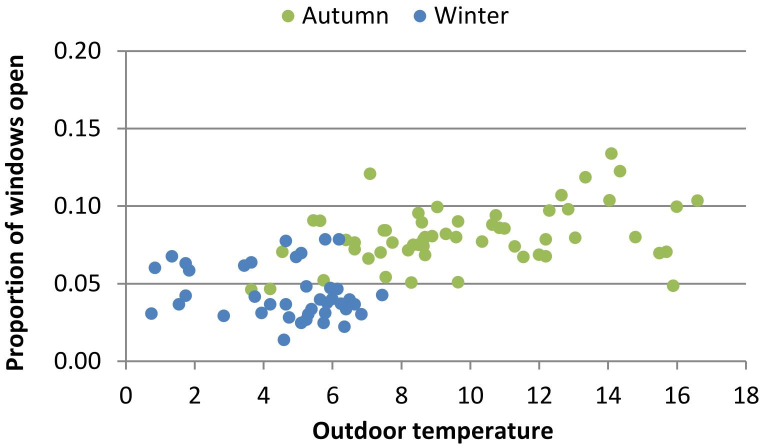


Figure 4-5: Variation of proportion of windows open with outdoor temperature in autumn and winter

The average proportion of open windows in the summer was 36.4%, in the autumn it was 8.1% % and in the winter this was 4.3%. There was an accumulation of data points below approximately 5% of windows open for temperatures up to about 7°C. This indicates that at the lower temperatures recorded during this photographic survey, most windows remain closed, however a small proportion of windows also remained open regardless of the outdoor temperature.

An important observation made from the data recorded was the gap in the proportion of windows open between the autumn and summer observation periods. A possible explanation for this gap is the lack of data from the spring season. Herkel *et al.* (2008) suggested that even if the temperature in different seasons is the same, occupants will behaviour differently. For instance behaviour on a cold summer day will differ from behaviour on a warm winter day. Therefore, even though temperatures may be similar in spring and autumn seasons, the previous thermal experience may influence the present thermal comfort behaviour. Temperatures in spring may feel warmer compared to similar temperatures in autumn because of the previous experience of colder conditions in the winter season. The adaptive thermal comfort model is based on the idea that thermal history influences occupant's thermal expectation and preferences (de Dear & Brager 1998). Experience affects expectations and expectation is what the environment should be, not what it actually is. Based on this, people's previous thermal experience will have an impact on their current thermal state (Nikolopoulou & Steemers 2003). The possible impact of thermal history that affect occupant's thermal comfort and hence window opening behaviour will be discussed further in Section 5.7.1 using observations made in the indoor survey.

Environmental information that is missing from the photographic survey is indoor conditions and factors that affect the indoor environmental conditions. Factors such as solar gain and mean radiant temperature are parameters that can influence window opening as they have an impact on indoor thermal conditions. An occupant's thermal comfort can be affected by the presence of hot or cold surfaces in the room. Mean radiant temperature (MRT) which is one of six main variables responsible for thermal comfort, is a means of expressing the impact of the temperature of the surrounding surfaces on the thermal comfort. MRT plays an important role particularly in spaces with large glazing areas and it can vary substantially from indoor air temperature. In winter, radiant heat loss toward a cold window surface and cold building materials can cause thermal discomfort due to a cooling sensation and in summer, radiant heat gain through solar gain can also cause thermal discomfort due to a warming sensation. The area of the surface and the angle factor, which is the geometric relationship between the occupant and each surface in the room, will have an influence on the MRT. The influence of MRT will also vary across the room, depending on the distance of the surface from the occupant. For example, the MRT at or near the window and the walls will be different from that in the middle of the room and at or near the door which is on the other side of the room, opposite to the window.

Effects of thermal environments, which include the contribution of MRT, have been determined by thermal indices such as the predicted mean vote (PMV) (Fanger 1970) and the physiological equivalent temperature (PET) (Höppe 1999). Using PET measurements, Hermann and Matzarakis (2010), showed slight variation in the influence of MRT on thermal comfort between the spring and autumn seasons. In the spring, there were slightly more PET measurements corresponding to 'slightly warm', 'hot' and 'very hot' votes compared to the autumn season. The biggest variation in the thermal comfort votes was between the summer and the winter seasons. The variation in perceived thermal comfort in the spring and autumn seasons is a possible reason for the difference between the proportion of windows open in these seasons and this suggests that window opening behaviour in spring and autumn should be considered separately.

These factors also show how outdoor temperature and indoor thermal conditions are related to affect occupant thermal comfort and window opening behaviour. Indoor environmental conditions are therefore important to further explain observations and variations recorded in photographic surveys of occupant behaviour. Rijal *et al* (2007) noticed a difference of approximately 10% and 18% between the autumn and spring data in their longitudinal and transverse surveys respectively. In the longitudinal survey, the average proportion of windows open in the spring and autumn were approximately 0.38 and 0.28 respectively and in the transverse survey these figures were approximately 0.41 and 0.23. The difference they recorded in their transverse data corresponds to the gap observed in the current photographic survey. This observation further suggests that behaviour in spring and autumn should be considered separately as at the same temperatures, there is likely to be a higher proportion of windows open in spring compared to the autumn season, hence the gap in Figure 4-4 may be smaller.

4.5.3 Relative humidity

Generally the proportion of windows open decreased with increasing relative humidity. The variation in proportion of windows open with outdoor relative humidity is shown in Figure 4-6 and the data is filtered into autumn and winter in Figure 4-7. The decreasing trend in proportion of windows open with relative humidity is not very clear in the autumn and winter and the range of relative humidity recorded during these two observation periods were very similar. The average relative humidity recorded during the autumn and winter were 84% and 86% respectively.

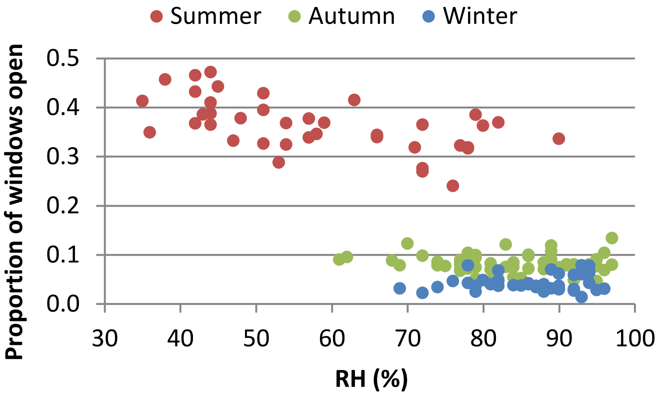


Figure 4-6: Variation of proportion of windows open with relative humidity

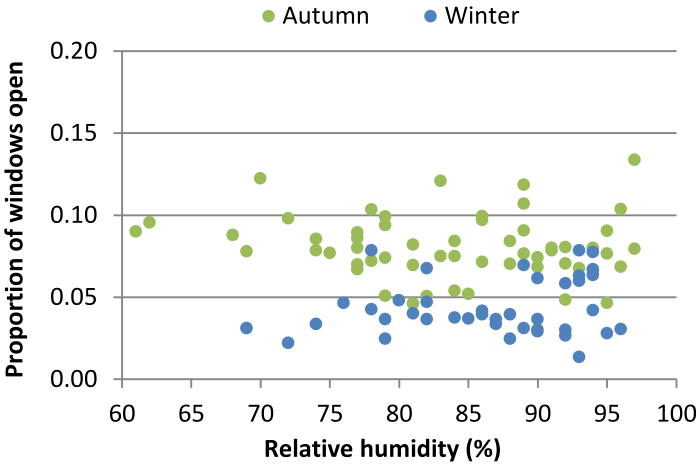


Figure 4-7: Variation of proportion of windows open with outdoor relative humidity in autumn and winter

4.5.4 Wind speed

The hourly average wind speed recorded in the summer ranged from 1.0 to 5.1m/s and in the autumn and winter wind speeds up to 7.2m/s were recorded. The relationship between the proportion of windows open and wind speed is presented in Figure 4-8. The figure shows a upper accumulation of the summer data points at wind speeds up to 3m/s and an accumulation of autumn and winter data points below 10%, especially as wind speed increases from 3m/s. Figure 4-9 shows a more clearer variation between the autumn and winter observations. The relationship between wind speed and proportion of windows open is slightly noticeable: at higher wind speeds the proportion of windows open is greater than at lower wind speeds..

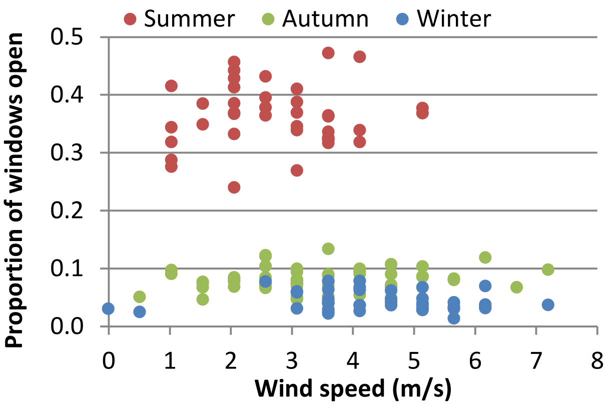


Figure 4-8: Variation of proportion of windows open with outdoor temperature

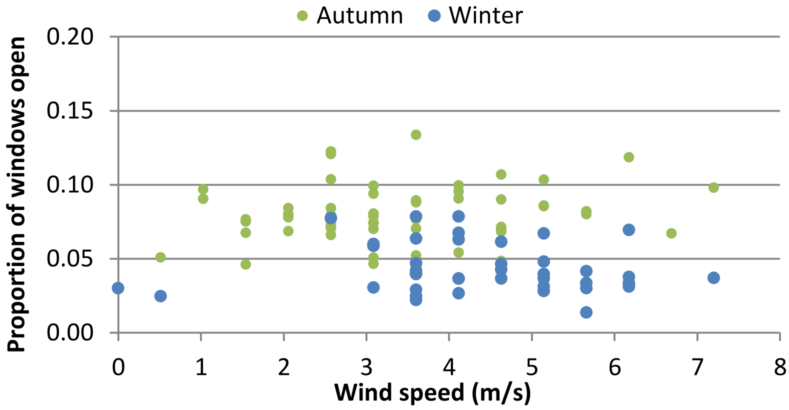


Figure 4-9: Variation of proportion of windows open with outdoor relative humidity in autumn and winter

4.5.5 Rainfall

As can be seen in Figure 4-10, it hardly rained during the summer observation period and the highest rainfall level was recorded in the autumn. This was a one-off observation during the survey period. Figure 4-11 presents the data from the autumn and winter observations during which increasing amounts of rainfall were recorded. This plot excludes the highest rainfall data point recorded in the autumn. Even though the proportion of windows recorded as open was higher in the autumn compared to the winter, very similar amounts of rainfall were recorded in during the two observation times. The relationship between proportion of windows open and rainfall is not noticeable in the data collected in this survey.

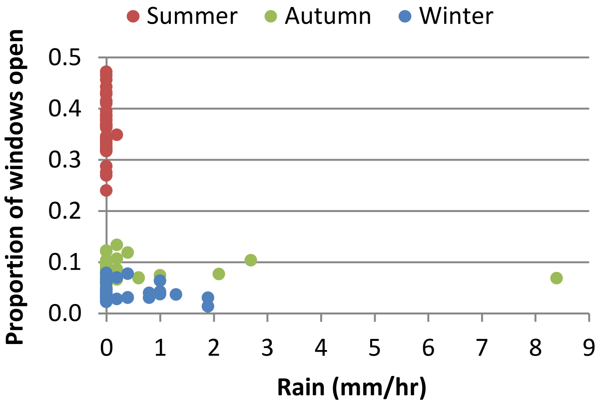


Figure 4-10: Variation of proportion of windows open with rainfall

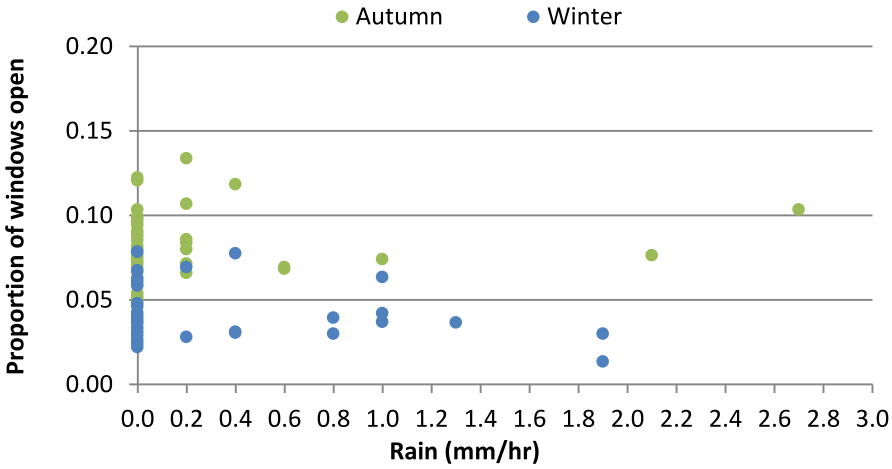


Figure 4-11: Variation of proportion of windows open with outdoor relative humidity in autumn and winter

The plots of proportion of windows open against the weather parameters show that during all observation periods, there were always a number of windows open, regardless of the outdoor temperature, relative humidity or wind speed. At the lowest temperature of 0.8°C in the winter period, 3% of the total windows were recorded as open and the minimum proportion of windows open was 1% (27 windows recorded as open).

4.5.6 Correlations between environmental variables and proportion of windows open

Data collected from all three seasons were put together to determine the correlations between the environmental variables and the windows open and the logistic regression parameters. This was to allow for the comparison with results from earlier studies. The data will be split into observations made in each season for a season specific analysis.

Pearson's correlations (r) between the weather parameters and the proportion of windows open are presented in Table 4-5. The correlation coefficients are used to measure the linear association between the dependent or outcome variable (proportion of windows open) and the independent or predictor variables (weather parameters). The magnitude and the sign of the coefficient indicate the strength and the direction of the relationship. Coefficients range from $r = -1$ to $r = 1$, and the larger the magnitude, the stronger the relationship between the variables. Negative values indicate that as the independent variable (the predictor variable) increases, the outcome variable decreases and positive values indicate that as the predictor increases, the outcome variable also increases.

The coefficient of determination (r^2), is obtained by squaring the correlation coefficient and gives the measure of the amount of variation in the outcome that is explained by the predictor. It can be seen that outdoor temperature has the strongest correlation with the proportion of windows open and this relationship is positive, indicating that as outdoor temperature increases, the proportion of windows open increases. This correlation coefficient is significant at a 0.01 level. Relative humidity, wind speed and rainfall are negatively correlated with open windows, indicating that as these parameters increase, the proportion of windows open decrease. The correlations between humidity and open windows and between wind speed and open windows were both statistically significant.

Table 4-5: Correlation between proportion of windows open and weather parameters

Weather parameter	**Pearson Correlation**	p	R^2
Temperature (°C)	0.901	< 0.01	0.812
RH (%)	-0.796	< 0.01	0.634
Wind speed (m/s)	-0.329	< 0.01	0.108
Rainfall (mm/hr)	-0.163	0.059	0.027

From the significance value, rainfall just misses out on being significantly correlated with the proportion of windows open. The calculated coefficient of determination for rainfall is

0.027. On its own, rainfall accounts for 2.7% of the variation observed in proportion of windows open. Compared to other weather parameters, this is quite small and according to the statistical analysis, it is not significant. The contribution of rainfall will be further assessed using logistic regression analysis due to the possible seasonal variation in window opening

4.5.7 Correlations between outdoor temperature and outdoor relative humidity (multicollinearity)

Relative humidity is the amount water vapour in the air relative to the amount of water the air can hold. Assuming that the amount of water vapour in the air remains the same, in lower temperatures, the amount of water vapour air can hold is reduced, hence as temperature decreases, relative humidity increases and vice versa. The correlation between measured outdoor temperature and outdoor relative humidity in the current survey is -0.81. This correlation is high enough to present a collinearity issue between the variables. High correlation or multicollinearity between the independence variables makes it difficult to estimate the effect on the dependent variable of one predictor variable over the other. The variance inflation factor between outdoor temperature and outdoor relative humidity was 2.8. This indicates that the standard error of temperature will be 1.7 times larger than what it will be if it is not correlated with outdoor relative humidity. For this reason, outdoor relative humidity will be excluded from the multivariate analysis.

4.6 Univariate analysis

Using the logistic regression analysis, the regression constants and coefficients were determined for each weather parameter in univariate models. These are presented in Table 4-6. As can be seen in Figure 4-10, the rainfall data contains a value that is an outlier causing a positive skew of the rainfall data. Transforming the rainfall data did not improve the positive skew of the data set therefore the statistical analysis was conducted with and without the outlier and the results were compared.

A statistical significance ($p < 0.001$) is observed for all the variables assessed. From the analysis, statistical significance was observed for all the weather parameters. The model with outdoor temperature had the highest likelihood ratio statistic and so it best describes the variation in proportion of open window.

Table 4-6: Regression parameters for univariate models

Variable	a	b
Outdoor temperature	-3.55±0.014	0.13±0.001
Outdoor relative humidity	1.75±0.020	-0.05±0.0003
Wind speed	-0.83±0.013	-0.26±0.004
Rainfall (with outlier)	-1.62±0.006	-0.66±0.020
Rainfall (without outlier)	-1.59±0.006	-1.28±0.028

Excluding the high rainfall value, the slope associated with rainfall was almost doubled that of the slope when the outlier was included. The former result indicates a stronger influence of rainfall on the proportion of windows open. The negative sign indicates that as the amount of rainfall increases, the proportion of windows open decreases. The data set without the outlier was retained for the remainder of the analysis.

4.6.1 Outdoor temperature

For outdoor temperature, the regression curve shows that the proportion of windows open increases significantly as outdoor temperature increases above 10°C. This is presented in Figure 4-12 which also shows the observed proportion of windows open.

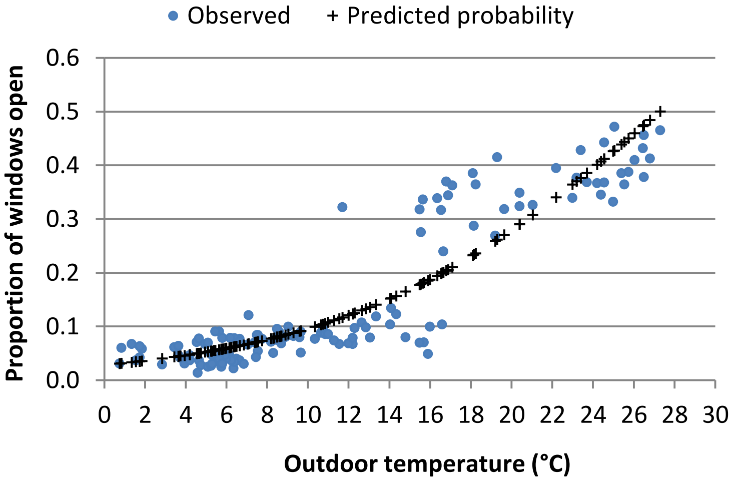


Figure 4-12: Observed proportion and predicted probabilities of windows open with outdoor temperature

The regression constants and the curves from earlier studies and the current study are presented in Table 4-7 and Figure 4-13. The previous studies presented here used either a photographic survey or an observation survey method to assess the influence of outdoor temperature in the proportions of windows open that they recorded. All of these studies were conducted in naturally ventilated office buildings. The regression curves have been plotted over an extended range of outdoor temperature for comparison. Warren and Parkins analysed the results from their observation using a linear regression method and so their probability line is not included in the graph. It is also worth noting here that only Haldi and Robinson's, Zhang and Barrett's and the current surveys were conducted in academic buildings. Nicol and Rijal's studies were conducted in other office buildings. Offices in academic buildings can have a different usage compared to offices in other buildings. Particularly in the summer, offices in an academic building may be under used or have lower occupancy rates due to the academic holidays compared to offices in other buildings where occupants may be able to take holidays at any time in the year. Also during the academic term time, the daily usage of offices in academic buildings may differ from usage of offices in other office buildings due to the teaching timetable. Occupancy patterns in academic buildings will therefore vary from that in other office buildings just as occupancy patterns in offices are different from that in residential buildings. Information on occupancy patterns is therefore useful when investigating the factors that influence window opening. An indoor survey that includes a record of occupancy patterns, either through a self-report or a motion logger, will be useful in order to determine exactly when the office is occupied.

Table 4-7: Regression parameters calculated from statistical analysis for outdoor temperature

Reference	**Description and analysis**	***a***	***b***
Warren and Parkins	Photographic survey Linear regression	-3.20	2.00
Nicol (UK)	Observation during thermal comfort	-2.65	0.17
Nicol (Europe)	survey	-2.31	0.10
Nicol (Pakistan)	Logistic regression	-3.73	0.12
Rijal *et al.* (trans - all)	Transverse survey	-2.92	0.16
Rilal *et al.* (trans - each)	Logistic regression	-3.80	0.16
Haldi and Robinson	Observation Logistic regression	-1.12	0.05
Zhang and Barrett	Photographic survey Logistic regression	-4.01	0.10
Current study	Photographic survey Logistic regression	-3.55	0.13

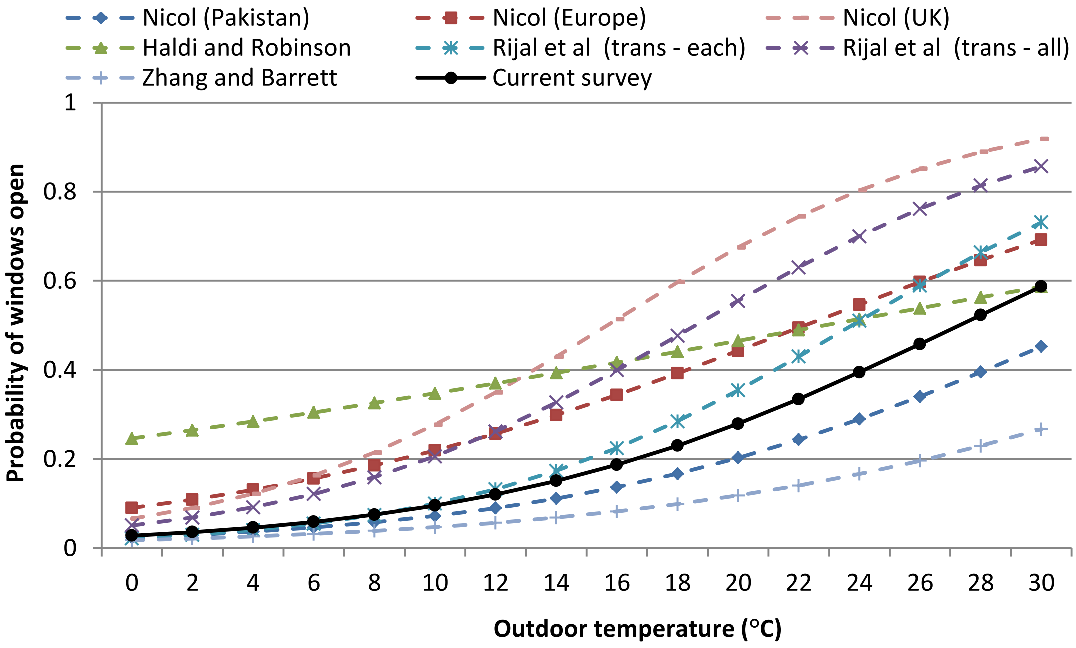


Figure 4-13: Comparison of probability of windows open as a response to outdoor temperature from previous study and current study

The continuous line represents the curve produced from the photographic survey conducted for the current thesis and the broken lines represent the curves produced from data collected in earlier studies. The regression curves plotted from the calculated regression parameters all show that the proportion of windows open increases as outdoor temperature increases with a steeper increase from temperatures above 10°C. Variation in the prediction of windows open is larger above 10°C. For instance at an outdoor temperature of 20°C, the predicted probability of windows open ranges from 0.12 (from Zhang and Barrett) to 0.67 (from Nicol – UK) with an average of 0.39. The difference between the models can be attributed to other factors that influence window opening such as other environmental variables (both indoor and outdoor) and non-environmental variables. This variability between models will be discussed further in Chapter 7.

4.6.2 Other weather variables

Figures 4-14 to 4-16 present the observation and the regression curves for proportions of windows open as a function of the measured outdoor relative humidity, wind speed and rainfall respectively. Decreasing proportions of opened windows are observed for increasing relative humidity, wind speed and rainfall. For relative humidity, there is also an accumulation of observed data points at humidity levels above 75%. Increase in average hourly wind speed and rainfall are also seen to be linked with a decrease in proportions of windows opened. The decrease due to these two parameters is less sharp compared to the influence of humidity and the scatter in the rainfall data is because some of the observation days, particularly in the autumn and winter, were very wet days, recording the increasing levels of rainfall.

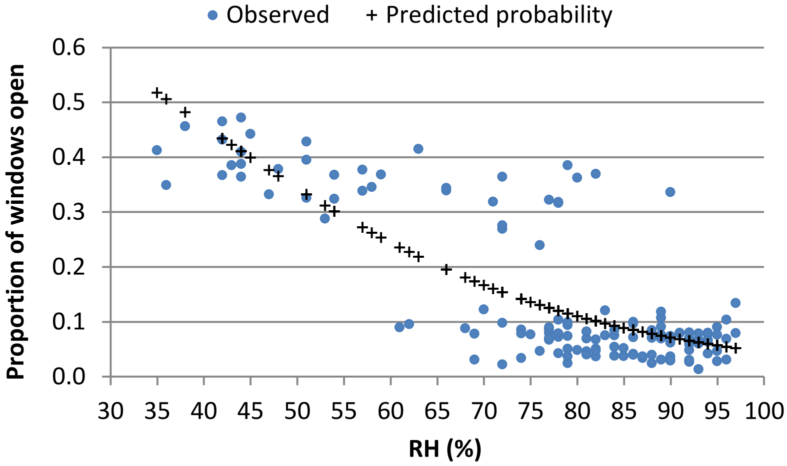


Figure 4-14: Observed proportion and predicted probabilities of windows opened as a function of relative humidity

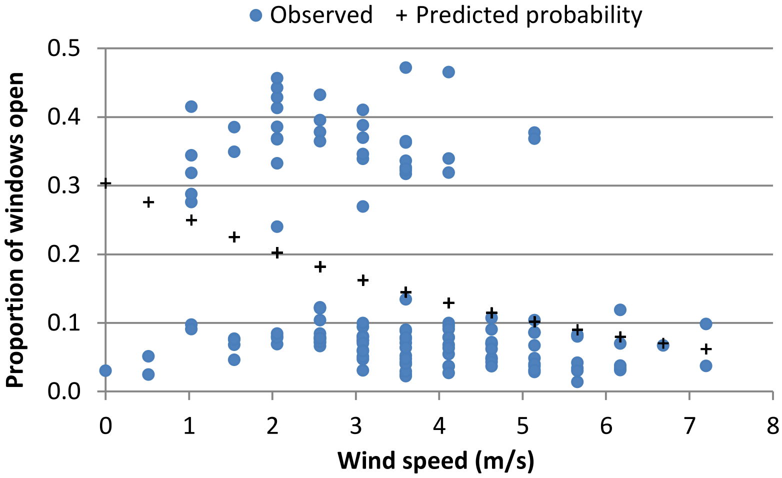


Figure 4-15: Observed proportion and predicted probabilities of windows opened as a function of wind speed

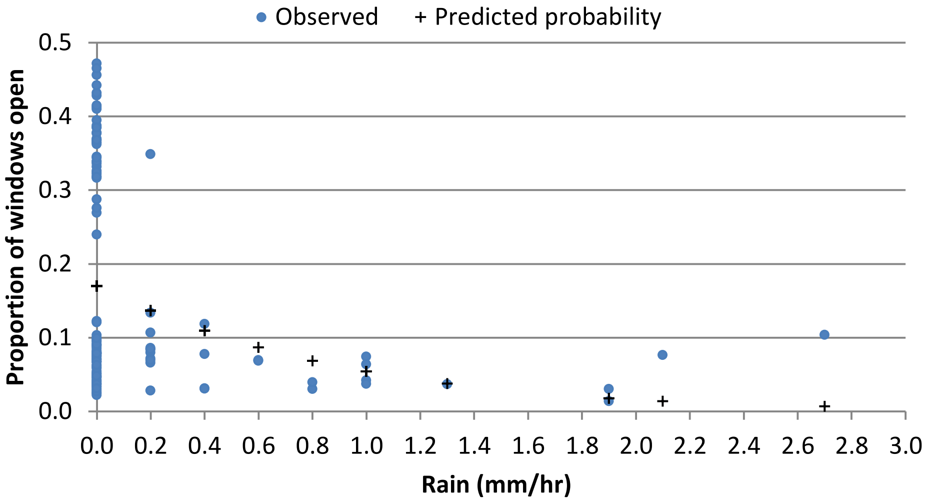


Figure 4-16: Observed proportion and predicted probabilities of windows opened as a function of rainfall

4.7 Multivariate analysis

From the univariate analysis, the best model containing two or more of the weather parameters was analysed. The Akaike Information Criterion (AIC) and the Likelihood Ratio (LR) parameters were calculated for each individual variable. These statistical parameters are useful as they provide a means for model selection from a set of models. Table 4-8 presents the likelihood ratio and AIC for the individual independent variables. Outdoor temperature had the highest likelihood ratio statistic and the lowest AIC value compared to the other variables, implying that it best describes the variation in the proportions of windows open.

Table 4-8: Likelihood ratio and Akaike information criterion calculated from the univariate analysis

Variable	**Likelihood ratio**	**Akaike information criterion**
Outdoor temperature	31316	7100
Relative humidity	23133	15283
Wind speed	4769	33647
Rainfall	3482	36376

Table 4-9 presents the regression results and the statistical tests for the goodness-of-fit for the multivariate models. In the multivariate analysis, outdoor temperature was retained as the primary variable and the improvement to the model by the addition of the other variables were assessed. With the exception of relative humidity, a statistical significance $p < 0.01$ was observed for all the variables in the models. With the addition of outdoor relative humidity, no further improvement was observed in the model. The regression coefficient and the likelihood ratio statistic for humidity were negligible and it was not a significant parameter in the final model ($b_{RH} = -0.00004 \pm 0.0006,\ p = 0.95$). The resulting AIC was greater than the initial AIC (model with temperature only). Since relative humidity was correlated with temperature, it can be excluded from the model and from further analysis as the predictive power of the model will not be affected. Outdoor temperature is a better predictor of proportion of windows open

With the addition of wind speed and rainfall, the reduced AIC values show that there was some improvement in the final model. However, temperature remained the dominant parameter as its regression coefficient remained the same, with low standard errors and higher likelihood ratio values compared to wind speed or rainfall. The model with temperature and wind speed performed better than the model with temperature and rainfall. In the analysis of temperature and rainfall, the validity of the final model was uncertain due to the very small improvement from the addition of rainfall. A possible explanation for this is that very low amounts of rainfall were recorded during the survey period. Over 75% of observation period, particularly in the summer, were dry days. The average rainfall was the same for the autumn and winter periods. There was very small variation in the proportion of windows open with increasing rainfall levels. For these reasons, outdoor temperature and wind speed were retained in the final model as they best described the variation in the observed proportion of windows open.

Table 4-9: Regression parameters for multivariate models

Model	**Regression constants and coefficients**		**Likelihood ratio**	**Akaike information criterion**
1	Constant (a)	-3.54 ± 0.06		
	Temperature (b_{To})	0.13 ± 0.001	8183	7100
	Relative humidity (b_{RH})	0.00	0.005	7102
2	Constant (a)	-3.15 ± 0.022		
	Temperature (b_{To})	0.13 ± 0.001	27051	7100
	Wind speed (b_{WS})	-0.10 ± 0.005	504	6598
3	Constant (a)	-3.47 ± 0.015		
	Temperature (b_{To})	0.13 ± 0.001	27936	7100
	Rain (b_{Ra})	-0.31 ± 0.025	181	6855

The logit distribution to describe the proportion of windows open based on outdoor temperature and wind speed is therefore expressed by equation 4-1.

$$log\left(\frac{p}{1-p}\right) = -3.15 + 0.13(T_o) - 0.1(W_s) \tag{4-1}$$

Where p is the probability of windows open is, T_o is outdoor temperature and W_s is wind speed.

4.8 Seasonal variation

Herkel *et al.* (2008) noticed that the seasonal changes in proportion of windows open did not correspond to any sharp changes in outdoor temperature and there was a seasonal variation in occupant window opening behaviour. Yun and Steemers's (2008) indoor survey of occupant window opening was conducted in a summer season hence they concluded that their findings only give insight to window use behaviour in the summer. Based on the observations by Herkel *et al.* (2008), Haldi and Robinson (2009) attempted to describe the effect of season on window. However, they did not find any significant improvement to their models due to seasonal changes. They observed the same logit distributions produced by outdoor temperature.

The data collected in the current photographic survey was filtered in order to conduct a season-specific analysis. The regression parameters for each independent variable calculated in the univariate analysis are presented in Table 4-10.

Table 4-10: Regression parameters for season-specific analysis in both buildings

Season	**Environmental parameters**	a	b	p
Summer	Outdoor temperature	-1.34 ± 0.040	0.04 ± 0.002	< 0.01
	Outdoor relative humidity	-0.05 ± 0.030	-0.01 ± 0.001	< 0.01
	Wind speed	-0.60 ± 0.020	0.02 ± 0.007	0.03
	Rainfall	-0.56 ± 0.008	-0.33 ± 0.251	0.17
Autumn	Outdoor temperature	-2.78 ± 0.040	0.03 ± 0.004	< 0.01
	Outdoor relative humidity	-1.88 ± 0.109	-0.01 ± 0.001	< 0.01
	Wind speed	-2.58 ± 0.031	0.03 ± 0.008	< 0.01
	Rainfall	-2.47 ± 0.013	0.02 ± 0.031	0.55
Winter	Outdoor temperature	-2.88 ± 0.047	-0.05 ± 0.010	< 0.01
	Outdoor relative humidity	-4.09 ± 0.225	0.01 ± 0.003	< 0.01
	Wind speed	-3.02 ± 0.055	-0.02 ± 0.012	0.14
	Rainfall	-3.04 ± 0.019	-0.22 ± 0.037	< 0.01

The influence of outdoor temperature was significant in all three cases. From the logistic regression analysis, outdoor temperature was positively linked with windows open in the summer and autumn but not in the winter. This implies that from the observations made in the winter, as outdoor temperature increases, the proportion of windows open decreases. A possible explanation for the negative impact of outdoor temperature on windows open in the winter could be that during this season, windows open may be dependent on indoor temperature due to heating via central heating systems in the buildings. High or increasing indoor temperatures may result in bigger differences between the indoor and outdoor temperatures. During times such as sudden transitions from outdoors into the indoors, occupants may open windows to cool the indoor space. In the winter season, window opening will be effective in reducing the indoor temperature as the outdoor temperature is more likely to be lower than the indoor temperature. However, the smallest range of outdoor temperature was recorded during the winter observation (0.8°C to 7.5°C) compared to the summer and autumn observation periods. This small variation can make it difficult, though not impossible, to observe an accurate influence of a variable on windows open. For the temperature range recorded in the winter period, the proportion of windows open recorded ranged from 0.013 to 0.078 and the relationship between this range of outdoor temperature and range of proportion of windows open is not clear, as can be seen in Figure 4-5. This was the case in an earlier survey of occupant behaviour where indoor temperature was included in the analysis of the factors that influence windows open due to the small variation recorded (Fritsch & Kohler 1990). More observations are required, particularly in winter to draw a conclusion on the results.

Wind speed was significantly but positively linked with windows open in the summer and autumn seasons, implying that as wind speed increases, the proportion of windows open increases. Window opening in these seasons may be due to thermal conditions, both indoor and outdoor temperatures. In winter, wind speed was negatively related to windows open however it was not a significant variable. Rainfall was not a significant variable in summer and autumn. Most days in the summer observation period were dry and so there was no noticeable pattern in rainfall with windows open. Increasing rainfall levels were recorded in the autumn and winter periods however the relationship between rainfall and windows open was not clear in autumn and only slightly noticeable in the winter. In the winter rainfall was a significant variable influencing windows open.

Due to the relationship between temperature and relative humidity, as expected the association between windows open and outdoor relative humidity was negative in the summer and autumn and positive in the winter (opposite to the influence of outdoor temperature). Outdoor relative humidity was excluded from the multivariate analysis to avoid collinearity issues between the variables.

The results from the season-specific analysis confirm that occupant window opening behaviour varies depending on the season and not just the temperature conditions alone. The observations and the analysis have showed that different variables influence windows open in different seasons. Bigger differences can be seen between the summer and winter seasons. Observations are required for the spring season to be able to compare occupant window opening behaviour in the spring and autumn seasons.

From the multivariate analysis, the regression parameters for the season-specific analysis are presented in Table 4-11. Wind speed was not significant in the summer and autumn seasons. Adding wind speed to the model which already contained outdoor temperature did not improve the model. The AIC remained the same and L.R. values for wind speed were very low in both season. Therefore from the observations made in this photographic survey, outdoor temperature is the only driver for windows open in summer and autumn season.

In winter, outdoor temperature and rainfall were used in the multivariate analysis as these were the significant variables in the univariate model. Both variables were significant drivers of windows open, however, both were negatively linked to windows open, implying that as outdoor temperature and rainfall increase, the proportion of windows open decreases. Statistically, rainfall was the stronger predictor of windows open as it had the lower AIC and higher L.R. values.

Table 4-11: Regression parameters for season-dependent analysis

Season	**Regression constants and coefficients**		p	**Likelihood ratio**	**Akaike information Criterion**
Summer	Constant (a)	-1.34±0.04			
	Temperature (b_{To})	0.04±0.002	< 0.001	402	854
	Wind speed (b_{Ws})	-0.002±0.007	0.74	0.113	855
Autumn	Constant (a)	-2.80 ± 0.04			
	Temperature (b_{To})	0.03±0.004	< 0.001	56	705
	Wind speed (b_{Ws})	-0.002±0.007	0.21	1.60	705
Winter	Constant (a)	-2.84±0.047			
	Temperature (b_{To})	-0.04±0.010	< 0.001	21	754
	Rainfall (b_{Ra})	-0.22±0.038	< 0.001	36	720

4.8.1 Wind speed at different heights

Wind speed in urban locations is affected by obstacles such as buildings (orientation and height) and trees. Due to the high rise nature of Building 2, wind speed was considered in more detail, adjusting for the terrain and the height of the building. Equation 4-2 below was used to calculate the wind speed at the site of Building with constants for a city terrain.

$$v_s = v_m k z^a \tag{4-2}$$

Where v_s is the wind speed at the site of Building 2, v_m is the wind speed measured at the weather station, z is the building height and k and a are the constants that depend on the terrain. For a urban terrain, k and a are 0.21 and 0.33 respectively (CIBSE 2006). The floors in Building 2 were divided into six heights all of three floors each and the influence of wind speed at each level was analysed in a season-specific analysis. The regression parameters obtained from the univariate analysis of wind speed at different heights are presented in Table 4-12.

Table 4-12: Regression parameters for wind speed at different heights on Building 2

Season	**Floors**	a	b	p
Summer	1 – 3	-0.58 ± 0.088	0.01 ± 0.037	0.795
	4 – 6	-0.29 ± 0.079	0.05 ± 0.031	0.137
	7 – 9	-0.39 ± 0.072	0.01 ± 0.027	0.805
	10 – 12	-0.66 ± 0.074	0.03 ± 0.026	0.291
	13 – 15	-0.72 ± 0.739	0.06 ± 0.025	0.023
	16 – 18	-0.88 ± 0.077	0.02 ± 0.025	0.338
Autumn	1 – 3	-1.97 ± 0.064	0.02 ± 0.021	0.334
	4 – 6	-1.81 ± 0.055	0.03 ± 0.017	0.088
	7 – 9	-1.69 ± 0.048	0.02 ± 0.014	0.703
	10 – 12	-1.32 ± 0.382	0.02 ± 0.106	0.035
	13 – 15	-1.56 ± 0.459	-0.01 ± 0.013	0.279
	16 – 18	-1.35 ± 0.041	-0.13 ± 0.011	0.259
Winter	1 – 3	-3.65 ± 0.275	0.02 ± 0.078	0.755
	4 – 6	-4.01 ± 0.266	0.15 ± 0.068	0.320
	7 – 9	-3.80 ± 0.251	0.02 ± 0.062	0.696
	10 – 12	-2.95 ± 0.169	0.03 ± 0.040	0.495
	13 – 15	-2.67 ± 0.164	-0.06 ± 0.038	0.122
	16 – 18	-2.80 ± 0.175	-0.06 ± 0.040	0.113

In the summer, wind speed was only significant for floors 13 – 15, showing a positive link with the proportion of windows open. In the autumn, the wind speed was significant for floors 10 – 12. Similar to the observation in the summer, the proportion of windows open increases with increasing wind speed for these floors in the autumn. This observation suggests that other factors such as temperature may be the dominant factor influencing window opening. For floors 13 – 15 and 16 – 18, the influence of wind speed was not significant, however, the regression coefficient for wind speed was negative, implying that as wind speed increased, the proportion of windows open decreased. In winter, the influence of wind speed was not significant at any of the floor levels but similar to the results obtained for floors 13 – 15 and 16 – 18 in autumn, wind speed was negatively related to the proportion of windows open.

Floors 15 to 18 consist primarily of large studio spaces which are multiple occupancy rooms. Occupant behaviour in regards to window use will be different in these spaces compared to the single person rooms in which the occupant has sole control over the environment. The studio spaces are used mainly by students and so the occupancy level will be low during the summer. During the autumn and winter when these spaces are occupied, the windows may be closed to avoid high air speeds in the rooms. The width of the window opening and wind direction may also have an influence on window opening as these factors will impact on air speed through the rooms in the building Aside from temperature, characteristics of the microclimate such as external noise and pollution levels may also have an impact on window opening behaviour.

The high p values for these floors could be due to the limited sample sizes used in the analysis (from splitting the data into floors). More observations of window states and wind speeds and from other high rise buildings may be required in order to draw a general conclusion on the impact of wind speed at different heights on window opening behaviour.

4.9 Other factors to be considered

The differences in the proportions of windows open due to non-environmental factors were investigated. The factors examined were buildings, façade orientation and design and room type. Due to the dominant impact of outdoor temperature, the influence of outdoor temperature was used to assess the differences.

4.9.1 Building specific

The data collected was filtered into cases relating to the individual buildings investigated. On average, there was a small difference in the proportions of window open between the buildings. The maximum number of windows open in Building 1 was 231, accounting for 49.8% of windows in the building. In Building 2, the maximum number of windows open was 714, accounting to 46.0% of total windows. The building specific analysis showed only a slight variation in the two buildings. Figure 4-17 present the probability of windows open for both buildings. The curves have been plotted over the outdoor temperature recorded during the survey period. Figure 4-17 shows that the probability of windows open is only slightly higher in Building 1 at temperatures up to 23°C. Above this, the probability of windows opened is higher in Building 2. This slight variation could be due to differences in the immediate area surrounding the building, building characteristics or differences in occupant characteristics which has an impact on the indoor environment.

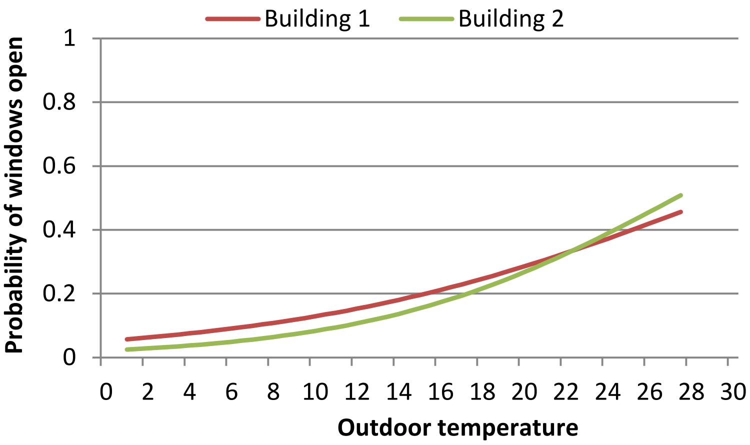


Figure 4-17: Building specific variation in probability of windows open with outdoor temperature

Even though the case buildings used in this study are in close proximity of each other, there are slight differences in the localised environment. Factors such as external noise and pollution levels may affect how occupants use building controls such as windows. As described in Section 3.2.1, Building 1 is bordered by a heavily trafficked roundabout on the city ringroad and two busy roads compared to Building 2 which is only bordered by one road. The main reason for the installation of the double-skin façade was to reduce the noise transfer from the road into the offices. Comparing window use in Buildings 1 and 2, Figure 4-17 suggests that there may not have been a difference in window opening due to external noise levels occurring at the site of the buildings. There was however no measurements of noise levels in this survey hence a conclusion cannot be drawn. One other benefit of the double-skin façade is the prevention of transfer of pollution and dust into the office. Again, the similarity between the window opening patterns in both buildings suggests that these factors of the localised environment may not have affected window use in the current survey.

Building characteristics such as the construction type of Building 1 (heavyweight construction with exposed structural elements) can increase the effectiveness of night ventilation in cooling the building during the day. For this reason, during the higher temperatures, occupants in Building 1 may not need to change their window opening behaviour as much as occupants in Building 2. If night time ventilation is not effective in Building 2, overheating may be a problem when outdoor temperatures are high and so the proportion of windows open may increase more sharply with the intention of increasing airflow to reduce the indoor temperature.

4.9.2 Room specific

The data was further filtered into room types in the building: single occupancy rooms (offices for academic staff), multiple occupancy rooms (meeting/seminar rooms, general offices, research offices) and 'other' rooms (corridors, rest rooms, kitchens and stairwells). Both buildings contain all of these types of rooms. Single occupancy rooms make up 36.5% (190), multiple occupancy rooms make up 41.0% (213) and 'other' rooms make up 22.5% (117) of the total rooms. For multiple occupancy rooms, spaces such as general offices and research offices will have different uses to spaces like meeting and seminar rooms. In the general offices and research offices, occupants are more likely to have permanent work places and hence these rooms will be occupied more often and for longer periods of time compared to the meeting/seminar rooms. In the meeting/seminar rooms, occupancy will be intermittent with occupants staying for shorter periods of time. Unfortunately the type of room based on its use were not differentiated on the floor plans and so these rooms have all being grouped as one for the analysis.

On average, the proportion of windows opened in 'other' rooms was higher than in single and multiple occupancy rooms. This was observed at all observation times and in both buildings. Multiple occupancy rooms recorded the lowest number of opened windows. Due to outdoor temperature, the result of the room specific analysis shown in Figure 4-18 also predicts that windows in 'other' rooms tend to be open slightly more often than in the single and multiple occupancy rooms. However, the differences is very small and the pattern of increase in windows open with outdoor temperature is identical, with proportion of windows open increasing at a higher rate at temperatures above 10°C.

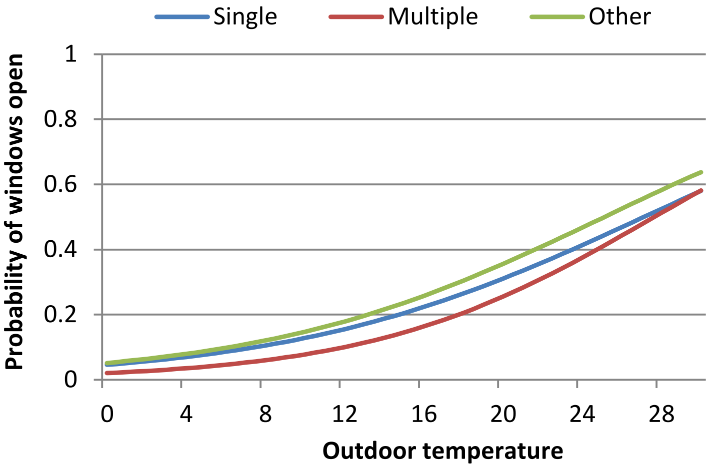


Figure 4-18: Room specific variation in probability of windows open with outdoor temperature in Building 1 and Building 2

Even though the slopes for the room specific curves are similar with no significant differences, several possible assumptions can be discussed for the different types of rooms in these buildings. In spaces such as the rest rooms and kitchens, the cleaners may open the windows when they arrive in the morning to carry out their duties. These windows may be left opened during the day to get rid of any unpleasant smells. Also, occupancy levels and duration in these spaces are often low and very short and so occupants may not be in there long enough to feel uncomfortable or to want to adjust the environment to affect their comfort/discomfort. Since occupancy in these spaces is intermittent and the spaces are not 'owned' by anyone in particular, occupants may not feel responsible for the windows so once a window is opened it is likely to remain opened for longer periods of time. In the multiple occupancy rooms such as meeting and seminar rooms, the rooms may only be occupied for short amounts of time and by different groups of people. Other multiple occupancy rooms such as research offices and administration offices may have longer occupation times with regular occupants who are familiar with the space. In the meeting/seminar rooms, windows may be used only during these short occupancy periods. Haldi and Robinson (2009) suggested that in multiple occupancy offices, there is the possibility that the window state may be set by the dominant or the most assertive occupant. In these offices, the assertive occupant may set the window state but this may be changed when an occupant in the room is not comfortable. In single occupancy offices, the occupant has sole control over their environment and the use of building controls such as windows. Yun and Steemers (2008) observed that changes in window state mainly occurred on arrival and at departure. Once a window state is set, it remained almost unchanged for most of the time between arrival and departure. Rijal *et al*. (2007) described occupants as ‘active’ or ‘passive’ and showed that the proportion of windows opened was higher among active occupants than passive occupants. Therefore, in single occupancy offices with active occupants, the windows are more likely to be opened and remain opened.

Regardless of these, it has been established that outdoor temperature has an influence on window opening and an increase in this parameter will result in an increase in window opening. Even with the very slight differences, this is confirmed for all room types in the buildings investigated in this study.

4.9.3 Façade orientation and design

Other factors that were considered were the orientation of the building façades and the façade design. These factors were considered to examine any possible differences in the proportion of windows open due to the surroundings of the buildings. Comparisons were made between façades alongside the busy roads and those on the courtyard side and between the single-skinned and the double-skinned façades.

Building 1 has 16 façades and although some of the façades are tilted some degrees in the clockwise and anticlockwise directions, the façades have been grouped into north, south, east and west orientations. Two of the façades are tilted approximately 45° and so they have been maintained as north-west and south-east façades. Building 2 is a rectangular shaped building whose long axis is oriented approximately 20° anticlockwise. The façades of this building have been classed as north, south, east and west orientations.

From the observed data, the maximum mean proportions of opened windows recorded in the summer occurred on the south (45.4%) and west (42.2%) façades. In the summer, the south façades receives the highest amount of sun light and hence increasing solar gains may cause the rooms to heat up quickly. Occupants in rooms on this façade may open the windows more frequently in an attempt to improve the thermal conditions. The west façade also receives a considerable amount of sun light in the afternoon, especially during the summer season, and so this may also be a reason for the high proportion of opened windows.

The lowest mean proportion of opened windows was recorded on the north façade (25.2%). The north façade receives the least amount of sun light and so rooms on this façade may be cooler. Occupants in rooms on this side may therefore not use the windows as often if windows are used primarily to improve discomfort due to thermal conditions.

From the façade specific analysis the regression coefficients and curves were calculated and plotted for all the façades. The regression parameters and resulting curves are presented in Table 4-12 and Figure 4-19. Figure 4-19 shows that the predicted proportion of windows opened is highest on the south and west façades at temperatures greater than 16°C. For the north façade, the proportion of windows opened starts to increase at a slightly higher temperature (about 19°C).

As mentioned before, the North West (NW) and the South East (SE) façades only relates to Building 1. The rooms on the NW façade are single occupancy offices and multiple occupancy research offices. On the SE façade, 60% of the windows are in the stairwells and the rest rooms. Average proportions of windows opened recorded for the summer, autumn and winter seasons were 25.1%, 20.5% and 15.3% respectively. The value for winter on this façade was the highest recorded for all the façades in total. The windows that were frequently opened on this façade were the stairwell and rest rooms windows. This was regardless of the outdoor temperature, a possible reason for the high predicted proportion of opened windows at the lower temperatures and also the small slope for the calculated regression curve for the façade.

Table 4-13: Regression parameters for the different façade orientations for both buildings

Façade type	a	b
North	-3.98 ± 0.03	0.13 ± 0.002
South	-3.64 ± 0.03	0.15 ± 0.001
East	-3.23 ± 0.03	0.11 ± 0.002
West	-3.65 ± 0.04	0.15 ± 0.002
North west (NW)	-2.69 ± 0.07	0.09 ± 0.004
South east (SE)	-1.71 ± 0.09	0.03 ± 0.006

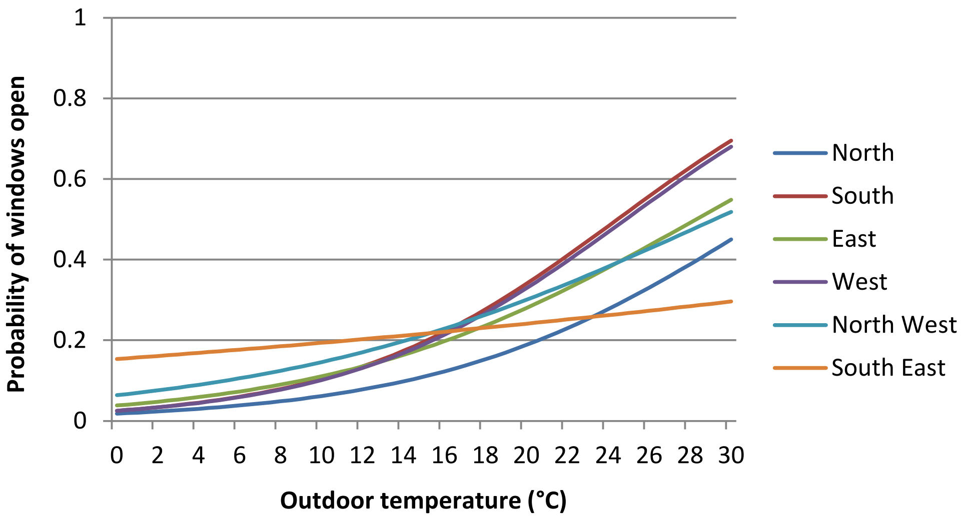


Figure 4-19: Façade specific variation in probability of windows open with outdoor temperature in Building 1 and Building 2

Building 1 has a double skin façade on the west façade (ring road side) and a single skin façade on the east façade (court yard side) and so the façade design specific analysis was only conducted on this building. Figure 4-20 shows the variation in windows open with outdoor temperature which were plotted from the regression parameters in Table 4-13. The regression curve shows that the proportion of windows open as a result of increasing outdoor temperature is higher on the single skin façade side of the building compared to the double skin façade side. The difference in calculated regression coefficients is very small but it implies that window opening is slightly more dependent on outdoor temperature on the single skin side compared to the double skin side. Figure 4-21 presents the average proportions of windows open at the times of observation during the survey. Not only are the proportions of windows open higher on the single skin façade side but the average change in proportion of window open at each time of observation is also higher on the single skin façade side compared to the double skin façade side. The biggest change is observed during the last observation time. At this time, the proportion of windows open is reduced by 3.8% on the double skin façade and by 7.2% single skin façade. Even though windows can be left opened over night for night ventilation, occupants on the single skin façade side may close their windows on departure for protection from elements of the weather such as rain. Between 10:30 and 13:30, the difference was much smaller. Average proportions of windows open increased by 1.3% on the single skin façade and by 0.6% on the double skin façade. For these observations times, one possibility is to assume that occupants on the single skin façade are more exposed to changes in the weather conditions such as outdoor temperature changes or to other outdoor conditions such as noise and so they are therefore likely to use their windows more frequently than occupants in rooms on the double skin façade side of the building.

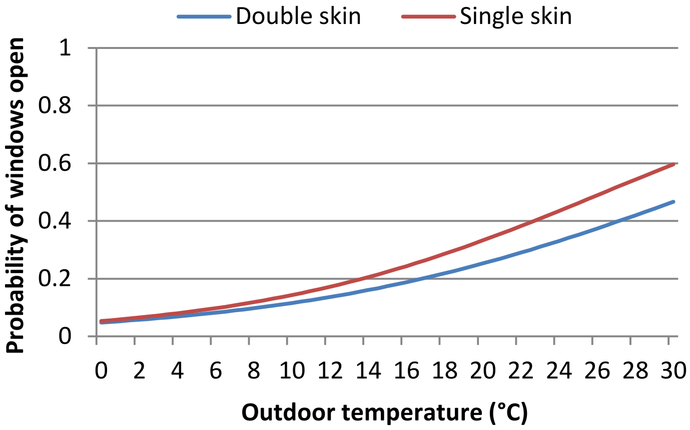


Figure 4-20: Façade design specific window opening probability as a function of outdoor temperature in Building 1

Table 4-14: Regression parameters for the different façade types

Façade type	***a***	***b***
Double skin	-2.99 ± 0.035	0.10 ± 0.002
Single skin	-2.88 ± 0.034	0.11 ± 0.002

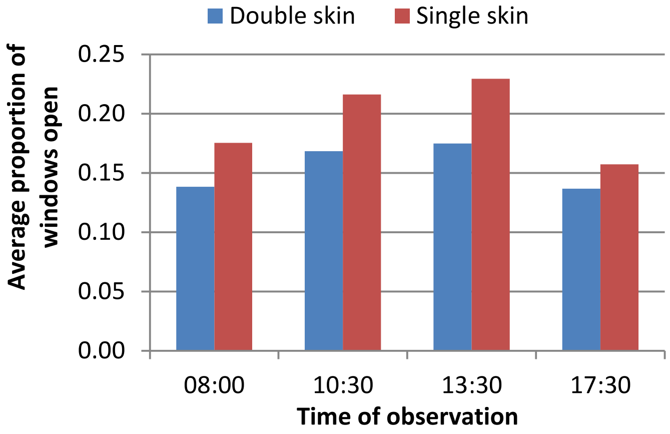


Figure 4-21: Average proportion of windows opened on each façade design in Building 1

4.10 Window state changing events

From recording the state of each window at all observation times, the proportion of windows that had changed state from the previous observation time was determined. The state changing events at the first observation time was determined from the state of the window recorded from the last observation time on the previous day, the state changing events at the second observation time was determined on the window state recorded from the first observation time and so on. It was noticed that only a small proportion of windows were actively used. Figures 4-22 and 4-23 present the proportions of recorded window changing states in the course of the day. At all observation times, approximately 96% of windows remained in the same state (either closed or open). For windows changing states, the highest closed to open events were recorded on the second observation time and the highest opened to closed events were recorded on the last observation time.

The maximum proportion of windows changing states was 5.0% and this was recorded at the 10:30 observation and the minimum proportion of windows changing states was 3.8% recorded at the 07:30 observation. The maximum proportion of windows changing from closed to open was 3.9% also recorded at 10:30 and the minimum was 0.7% at the 18:00 observation. Since the actual time of arrival was unknown in this photographic survey, it can be assumed that the period between the first and second observation times will contain some arrival and some intermittent occupancy periods, indicating that most window use, particularly window opening occurs on arrival and during intermittent periods. The maximum proportion of windows changing from open to closed was observed at 18:00 (4.0%).

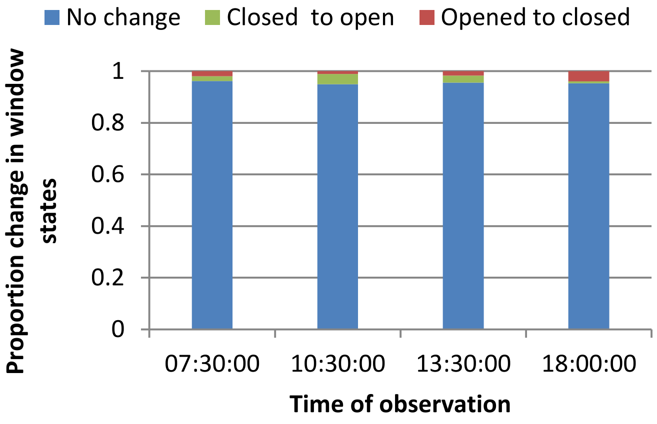


Figure 4-22: Proportion of window changing events at each observation time

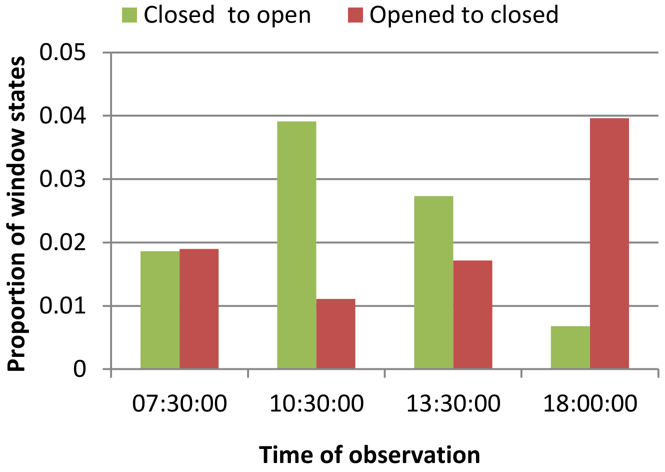


Figure 4-23: Proportion of windows changing from closed to open and from opened to closed

The data was filtered into the three observation periods (summer, autumn and winter seasons) and it was observed that window changing events occurred mainly in the summer season, followed by the autumn and then the winter season. In Figure 4-24 the proportions of window changing states are presented for each observation periods. The red bars represent window changing events in the summer, the green bars are the autumn events and the blue bars for the winter events. During the survey, at the first, second and third observation times, proportions of windows that had changed from closed to open were higher than windows that had changed from opened to closed. These observation times represent arrival and intermittent occupancy time period. In all three seasons, there was an increase in outdoor temperature between the first and third observation times. This increase was more noticeable in the summer period and only slight in the autumn and winter periods. At the last observation time, representing departure, the proportion of windows that had changed from opened to closed was greater than the closed to open events.

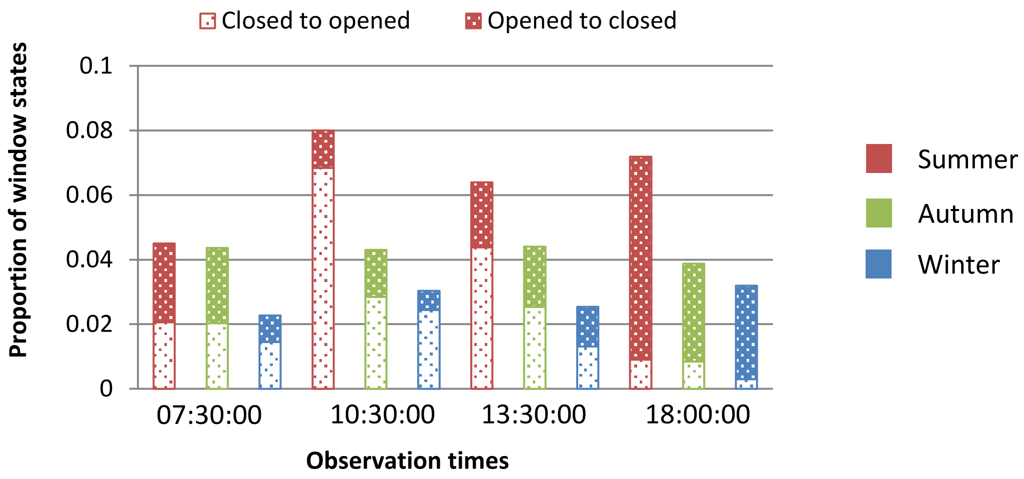


Figure 4-24: Window changing events recorded during the observation periods

4.10.1 Regression analysis for window state changing events

The influence of outdoor temperature and wind speed on window opening was investigated using logistic regression. The regression parameters for the analysis of windows changing from closed to open are presented in Table 4-14. These parameters were obtained in a univariate analysis. Both outdoor temperature and wind speed were significant parameters in the model.

Table 4-15: Regression parameters for window changing state in both buildings

Environmental variable	**Regression constants and coefficients**		**Likelihood ratio**	**Akaike information criterion**
Temperature	a	-4.42 ± 0.03		
	b_{To}	0.05 ± 0.002	863	2010
Wind speed	a	-2.39 ± 0.06		
	b_{Ws}	-0.39 ± 0.02	522	2351

In a multivariate analysis, the improvement to the model due to the addition of wind speed was assessed. The AIC value for the final model was 1970 indicating an improvement in the final model. The logit distribution to predict windows changing from closed to open, based on outdoor temperature and wind speed, is therefore expressed by equation 4-2. The regression coefficients indicate that as outdoor temperature increases and wind speed decreases, the proportion of windows changing from closed to open increases.

$$log\left(\frac{p}{1-p}\right) = -3.82 + 0.04(T_o) - 0.14(W_s) \tag{4-2}$$

4.11 Time dependent analysis

A time-dependent analysis was conducted to examine the influence of outdoor temperature on window changing events at the different observation times. Outdoor temperature was significant at a level of 0.001 for windows changing from closed to open at all the observation times. Figure 4-25 presents the regression curves and Table 4-15 presents the regression parameters used to plot the curves. The curves for the 10:30 and 13:30 observations times shows the biggest increase in proportion of windows changing from closed to open. The slope for 10:30 is also steeper compared the other three observation times. The observation at this time will include change in state on arrival and during intermittent period. These results indicate that windows are more likely to change from closed to open as outdoor temperature increases and also on arrival and during intermittent occupancy periods. At 07:30 and 18:00, the proportion of windows changing from closed to open is much lower and the slope is not steep, indicating that there is little window changing events at these times. At 07:30, most of the occupants may not have arrived yet and at 18:00, most occupants may have left for the day and the windows may be left in the same state.

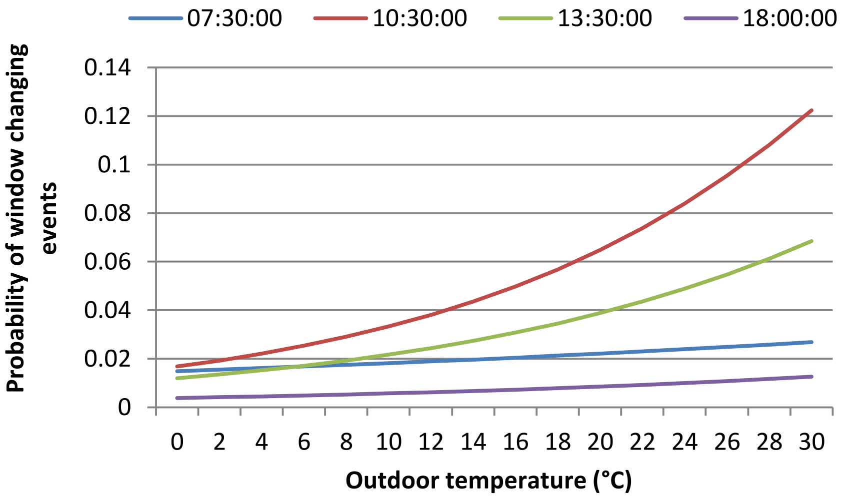


Figure 4-25: Predicted proportion of windows changing from closed to open at the observation times

Table 4-16: Regression parameters for time-dependent window changing state events

Observation time	a	b
07:30:00	-4.19 ± 0.07	0.02 ± 0.01
10:30:00	-4.09 ± 0.05	0.07 ± 0.003
13:30:00	-4.41 ± 0.06	0.06 ± 0.003
18:00:00	-5.56 ± 0.11	0.04 ± 0.007

4.12 Summary

The photographic survey conducted for this thesis allowed for the influence of weather conditions on windows open to be assessed. In total, 2004 windows were observed across two case study buildings in the summer, autumn and winter seasons. The weather variables investigated were temperature, relative humidity, wind speed and rainfall. The initial observation of the data collected showed a gap in the data which represents window use in the spring season suggesting that autumn and spring should be treated separated regardless of the similarities between outdoor temperatures in these seasons. Environmental factors such as solar gain and mean radiant temperature may have an impact on the indoor thermal conditions which could influence occupant thermal comfort and hence their window opening behaviour. Due to the strong correlation between temperature and relative humidity, the latter variable was excluded from the statistical analysis. In a univariate analysis of the entire data set, outdoor temperature was the dominant variable that influenced windows open; as outdoor temperature increased, the probability of windows in the open state also increases. The logistic regression curve obtained from the current observed data was plotted alongside those from earlier studies for comparison. The earlier studies used either the observation survey or the photographic survey. The variation in the probabilistic curves indicates that the selected survey method affects the results obtained. In a multivariate analysis, outdoor temperature and wind speed were significantly associated with window open.

In a season-specific analysis, different variables were associated with windows open in the different seasons: in summer and autumn, outdoor temperature and wind speed were significant and in the winter outdoor temperature and rainfall were significant. The influences of these significant variables were different in the seasons. In the summer and autumn, as outdoor temperature and wind speed increased, the probability of windows open increased. However, in the winter, probability of windows open increased with decreasing outdoor temperature and wind speed. The impact of wind speed at different window heights was assessed for Building 2 due to its high-rise nature. The results showed that in the autumn and winter, at the higher elevations (floors 13 to 18), although not significant in the current study, the probability of windows open increased with decreasing wind speed.

A time of day variation was observed and so the change in window states at each observation time was analysed. The highest proportion of window state change occurred between the first and the second observation times. Since these times overlap with typical arrival times, this result suggests that window opening occurs mainly during the arrival period. However, due to frequency of observation, actual window opening events on arrival cannot be determined. Slight variations were also observed between the buildings, room types and façade types and orientation.

The results confirm the influence of outdoor temperature and time of day variation on window opening. They also indicate that factors such as building parameters will play a role in predicting window opening behaviour. However, this photographic survey conducted for this thesis did not allow the investigation of indoor environmental variables. An indoor survey was therefore a useful method as it enabled the influence of indoor factors to be considered.

5 Indoor survey

5.1 Introduction

The general agreement in the observations and analysis from the previous studies is that thermal conditions are the main drivers for window opening. In chapter 4, the influence of weather conditions was investigated and a relationship between outdoor temperature and window position presented. Following on from this study in this chapter a more in-depth study of a smaller number of offices is carried out to investigate the role of both indoor and outdoor conditions. Relationships between indoor air temperature and window opening have been described by previous authors. However, as shown in Chapter 2, the resulting models developed vary quite significantly, and previous studies have often only measured a limited amount of indoor variables (e.g. temperature only). Therefore, in this chapter an indoor survey will be carried out focusing on a wider range of indoor environmental conditions: temperature, CO_2 concentration and relative humidity. Time of day and seasonal effects will again be analysed. As well as these, in the indoor survey as the window states are measured continually it is possible to assess what the environmental conditions are when a window changes state. Therefore for the time of day analysis, a model of a window changing from closed to open will be developed.

5.2 Case study offices

The offices monitored were located in the two case study buildings described in Chapter 3. A total of seven offices were monitored during the survey period – four offices in Building 1 and three in Building 2. The offices were selected to provide a variety in façade design.. All the offices in each building have the same use and are similar in dimensions. In every office occupants have the possibility to open the window(s). All offices contain standard small power office equipment – desk top computer and/or laptop computer and a printer. The offices have one external wall with windows, a door on the opposite wall and are located along double-loaded corridors. Single-sided ventilation is possible by opening the windows. In both buildings, furniture arrangements are identical in all single occupancy offices. Blinds are used to shield against glare from the sun, particularly on the computer screen and also to minimise overheating. Table 5-1 presents the details of the offices and Figure 5-1 are pictures of typical offices in the case study buildings.

Table 5-1: Description of offices used in the current indoor survey

Building	Office	Orientation	Facade	Window type	Periods monitored
1	1	North-west	Double-skinned	Side hung	1 and 2
	2	North-west	Double-skinned	Side hung	1, 2 and 3
	3	North-west	Double-skinned	Side hung	1, 2 and 3
	4	North-east	Single-skinned	Tilt and Turn	2 and 3
2	5	South	Single-skinned	Vertical slider	1 and 2
	6	South	Single-skinned	Vertical slider	1, 2 and 3
	7	North	Single-skinned	Vertical slider	2 and 3

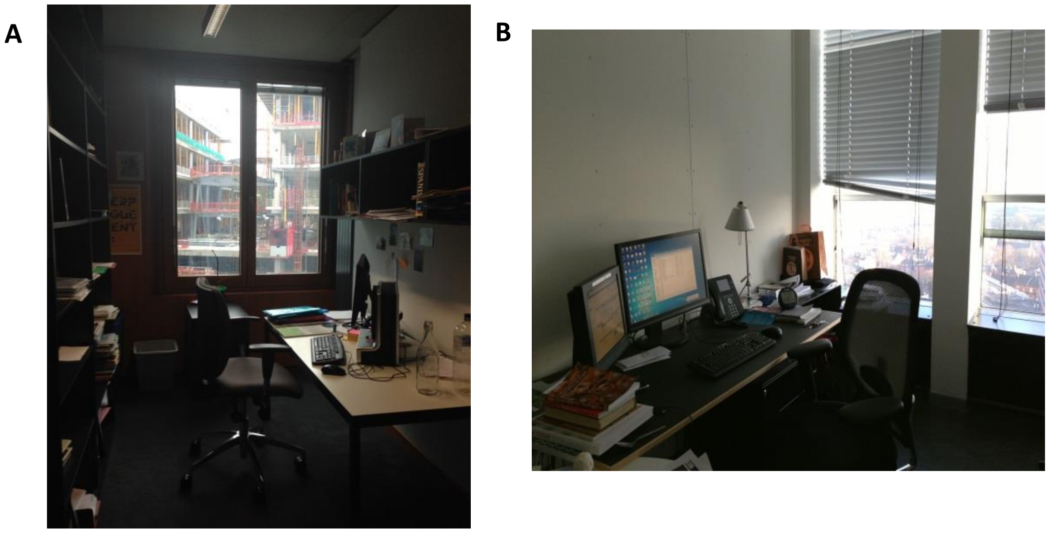


Figure 5-1: Photographs of case study offices: A– Office in Building 1; B– Office in Building 2

5.2.1 Office recruitment

The decision to conduct a monitoring survey is dependent on a number of considerations. The aim of the study and the intended outcome are important factors. However, available budget and the ability to recruit participants will also need to be considered. As discussed in Chapter 2, studies of window opening behaviour which have used indoor monitoring surveys often have small sample sizes. Sample sizes have ranged from four to 14 (Fritsch & Kohler 1990; Yun & Steemers 2008; Haldi & Robinson 2009). However more detailed information and environmental data can be collected (information on occupancy patterns, exact time of window state change, indoor environmental data in smaller time steps).

Several methods were used to recruit participants for the indoor survey described in this Chapter. The requirement for participation was that participants should have a permanent place of work in a single person office. Email canvassing was the initial method used to approach potential participants. Response to the email was followed up by meetings with the respondent to provide further information about the study. From the email and meetings, four participants were recruited. A further three potential participants were recommended and they were approached individually to request participation. The details of the study were also explained to the potential participants in a meeting. Details of the study – the aim, the duration of the survey and the equipment to be installed - were discussed with the participants. It was clearly explained that the survey would not cause any interference to working in the office and occupants could carry on with their activities as normal. Tasks such as downloading the data from the loggers would be pre-arranged with the participant so that it was done at a time convenient to them. Potential participants who replied to the emails and those who were approached individually all agreed to take part in the study and a gift voucher was awarded in appreciation of participation.

5.2.2 Offices in Building 1

Offices in Building 1 have a floor area of 8.84m^2. Offices 1 – 3 are oriented towards a busy road and therefore have the double-skinned façade. They have double side hung windows which open to the inside. Both panels in this window can be opened. In these offices, occupants can employ night ventilation strategy for cooling as the outer façade protects the office from elements of the weather and provides security. Office 4 faces a courtyard and has a single-skinned façade. The window in this office is a tilt and turn window and the occupants have the option to open up to an angle on the tilt or turn or to open wide like a side hung window. All occupants in this building are advised to open their windows a crack when ventilation is required.

5.2.3 Offices in Building 2

Offices in Building 2 have a floor area of 8.46m^2 each. All façades have the same type of façade design and windows. Each office has two windows which are single hung and slides downwards to open. Occupants have the option to open both windows if desired. There is the potential for night ventilation in this building as there are no security issues. However, there is no protection against elements of the weather during night time.

5.3 Survey methodology

An initial study period of one month in the summer (30 July – 31 August 2012) and one month in the winter (21 January – 22 February 2013) were selected to observe window opening behaviour in the selected offices. These duration periods were selected to monitor behaviour in two distinct thermal conditions. One month was selected to avoid sudden and/or significant changes in weather conditions which could alter occupant behaviour. Nicol (1992) showed evidence that occupants adapt almost completely in a week, however, this time period may not be sufficient to successfully capture occupant's behaviour due to occurrences such as planned or unplanned out-of-office periods. A month period would allow for window use behaviour to be observed in an environment where occupants spend a considerable amount of time, regardless of times when they may be out of the office for events such as meetings or days when they arrive later or leave earlier than their usual working hours. A third period of observation was included to coincide with the photographic survey period. This covered summer, autumn and winter seasons. Observations were made from July 2013 to February 2014.

5.3.1 Data acquisition

During the survey periods, weather data was obtained from the weather station described in Section 3.3 and indoor environmental conditions (air temperature, relative humidity and CO_2 concentration) were recorded using the data loggers described in Section 3.4. State loggers were mounted on the windows and door to record the time of opening. Information from the door state loggers was used to determine first arrival and last departure from the office. In the intermittent period (period between arrival and departure) door opening and closing were not considered.

5.3.2 Place of measurement of indoor conditions

The environmental data logger was placed on the desk of the occupant at a height of 0.76m above the floor to record conditions at five minute intervals. The logger was placed so it was not affected by factors such as incidence of direct sunlight, heat output from the computer and/or printer and expired air from the occupant. Since warm air rises, it is typical for air temperature to vary throughout the indoor space, with higher temperature at higher levels such as at the head than at the feet of the occupant. Olesen *et al*. (1978) showed that if the temperature difference is sufficiently large, warm discomfort can occur at the head and/or cold discomfort can occur at the feet. Percentage dissatisfied has also been shown to increase when air temperature increases upwards (Parsons 2003). This is typical for people in light sedentary activities such as office workers. Based on Olesen's work, a vertical air temperature difference of 3°C is the recommended limit for a height difference of 1m, typical of ankle (0.1m above ground) to head level (1.1m above ground) when seated (BS EN ISO7730 2006; ASHRAE 1992).

Since the logger was going to be placed on the table, a test was conducted to assess the difference in temperature between the floor and the table. Environmental loggers were placed on the table and on the floor to record air temperature at a sampling rate of 30 seconds. Temperature was recorded for a period of five hours, from 12 to 5pm, and the test was repeated two times. The logger on the table was placed directly above the logger on the floor in order to determine the vertical air temperature difference at these locations. Table 5-2 presents details of the temperatures measured. There was little variation between the temperatures recorded at the logger positions. As expected, the measurements recorded at the table level were greater than that at the floor level and the average difference in the readings was 0.56°C, which is only slightly higher than the sensitivity of the instruments. Placing the logger on the table will therefore be suitable to capture conditions affecting the occupant without missing conditions that cause significant discomfort.

Table 5-2: Descriptive data from temperature measurements

	Table	**Floor**	**Difference**
Minimum temperature (°C)	21.8	21.5	0.10
Maximum temperature (°C)	22.2	21.6	0.70
Mean temperature (°C)	22.1	21.5	0.56

5.4 Initial observations

First, the results will be presented correlating the environmental variables to the window state, allowing comparison to the photographic survey and a review of the impact survey method has on the results.

Second, the data is broken down to examine the factors that influence a change in window state. This uses data averaged over 5 minutes prior to a window changing state in order to assess the influence of the environmental variables on prompting window opening. The time period immediately prior to window opening is used in order to avoid accidently analysing the effect having a window open has on the indoor environment (e.g. diluting CO_2 concentration).

The descriptive statistics of all recorded environmental parameters which were used in the analysis are presented in Table 5-3. The data has also been presented for the periods when window states were either open or closed separately.

Table 5-3: Descriptive statistics of the environmental parameters recorded during the survey period

		T_{in} (°C)	CO_2 (ppm)	RH_{in} (%)	T_{out} (°C)	RH_{out} (%)	W_s (m/s)	S_o (hr)	R_a (mm/hr)
All data	Min	9.8	336	14.0	-2.1	28.0	0.0	0.0	0.0
	Max	34.8	3353	81.6	30.1	100.0	13.4	9.9	11.8
	Mean	22.3	644	40.3	10.6	80.6	3.6	3.6	0.12
	St Dev	2.4	271	10.1	5.7	12.3	2.0	3.1	0.50
Window opened	Min	9.8	336	14.0	-2.1	28.0	0.0	0.0	0.0
	Max	34.8	2552	81.6	30.1	100.0	12.9	9.9	11.8
	Mean	22.8	566	41.0	13.8	76.6	3.1	3.7	0.09
	St Dev	2.6	178	11.0	5.7	14.1	1.6	3.2	0.47
Window closed	Min	13.1	350	18.4	-1.1	36.0	0.0	0.0	0.0
	Max	30.4	3353	65.1	24.8	99.0	13.4	9.9	11.8
	Mean	21.7	726	39.6	8.2	83.5	3.9	3.3	0.15
	St Dev	2.0	325	9.1	4.4	9.7	2.2	2.9	0.52

5.4.1 Indoor environmental conditions

Recorded indoor air temperatures were binned over 0.5°C to create a histogram of exposure during occupied periods and this is presented in Figure 5-2. Higher frequencies of lower temperatures were recorded when windows were closed and higher frequencies of temperatures above 24.5°C were recorded when the windows were open. The mean and the standard deviation of indoor temperature were lower when the windows were closed compared to when they were opened. This standard deviation indicates a narrower distribution of temperatures around the mean when windows are closed.

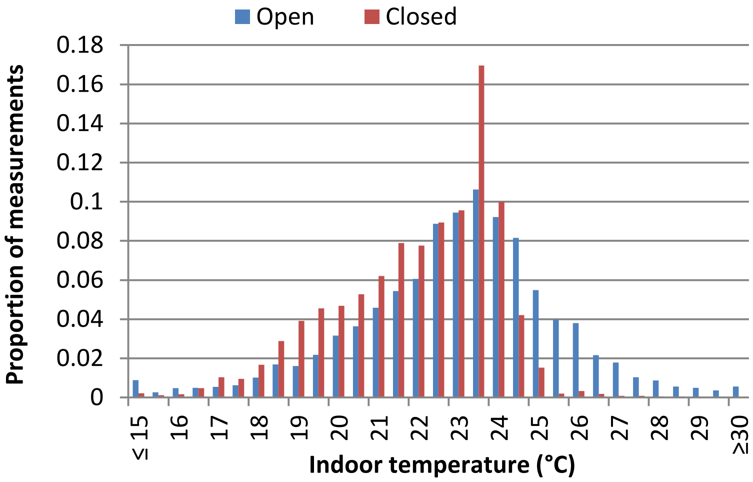


Figure 5-2: Indoor temperature when windows were open and closed

The complete CO_2 concentration recorded was binned over a range of 50ppm to produce histograms of exposure concentrations. The CO_2 concentrations recorded on occupied days are shown in Figure 5-3. The maximum CO_2 recorded was 3353ppm and the average was 644ppm. As expected lower CO_2 concentrations occurred more often when the window was opened and higher CO_2 concentration occurred more often when windows were closed. When windows are closed during times of occupancy, the rate of ventilation through the office may not be sufficient to reduce the CO_2 being generated by the occupant. CO_2 levels above 1500ppm made up 4% of the total data when windows were closed and 0.5% of the data when windows were open. The standard deviation for CO_2 concentration was also lower when the window was open compared to when they were closed indicating that CO_2 levels were maintained more closely around the mean of 566ppm when windows were open.

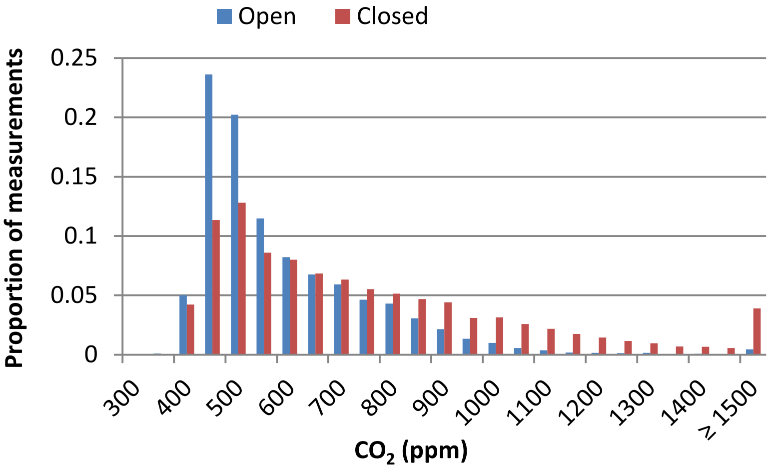


Figure 5-3: CO_2 concentration when windows were open and closed

The indoor relative humidity data was binned over a 2% range to produce histograms in Figure 5-4 indicating when windows are closed or open. Similar to indoor temperature, a higher frequency of lower relative humidity levels were recorded when windows were closed and slightly higher levels were recorded when windows were opened.

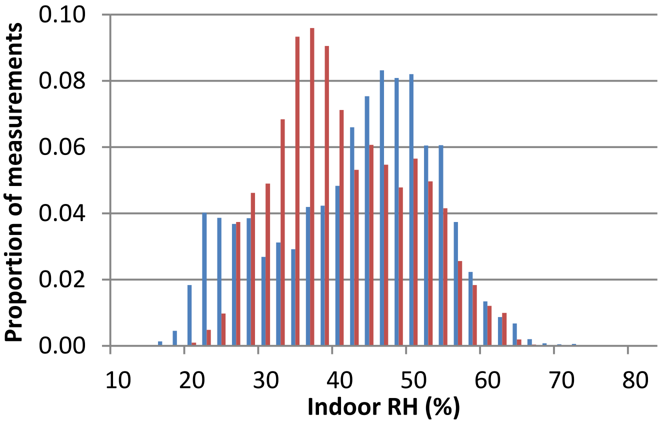


Figure 5-4: Indoor relative humidity when windows were open and closed

5.4.2 Outdoor environmental conditions

The data was filtered to include only times when the offices were occupied to produce the histograms of environmental conditions at which windows were opened and closed.

Figure 5-5 shows the proportion of window states at the measured outdoor temperature. A clear difference was observed in the temperatures recorded for the window states. A higher frequency of lower outdoor temperatures were recorded when windows were closed and higher temperatures were recorded when windows were opened.

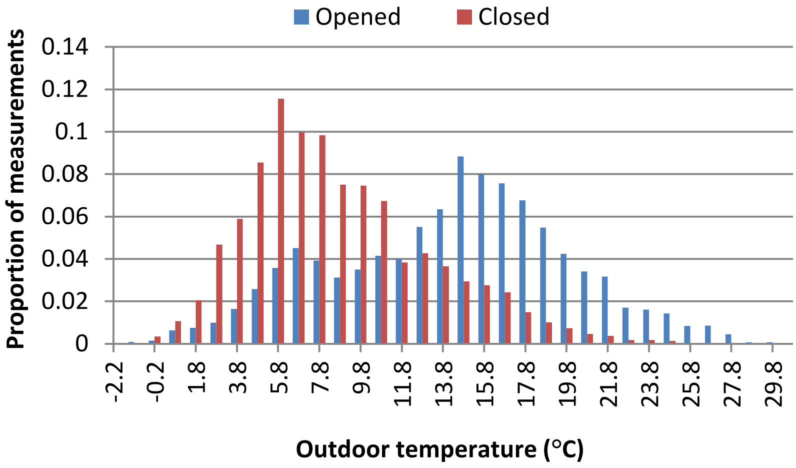


Figure 5-5: Outdoor temperatures when windows were open and closed

Outdoor relative humidity ranged from 28% to 100% with an average of 81%. There was little difference in the summer and winter measurements. The average outdoor relative humidity recorded in the summer was 79% and in the winter it was 83%. Figure 5-6 is a histogram of the recorded outdoor relative humidity at windows open and closed. The data was binned over a 2% range.

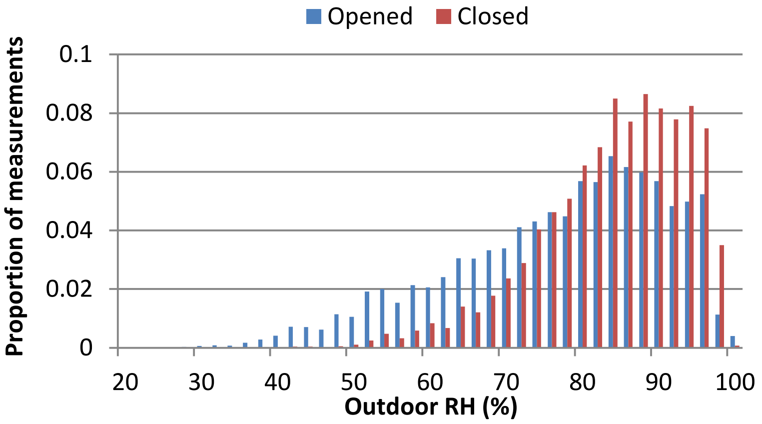


Figure 5-6: Outdoor relative humidity when windows were open and closed

Wind speeds observed during the monitoring period ranged from 0m/s to 13.4m/s. The minimum and maximum average wind speeds were recorded in the summer and winter season respectively. The recorded wind speed data was binned over a 0.5m/s range to produce the histograms shown in Figure 5-7. The wind speed distributions for windows open and closed show that a higher proportion of windows were closed at higher wind speeds.

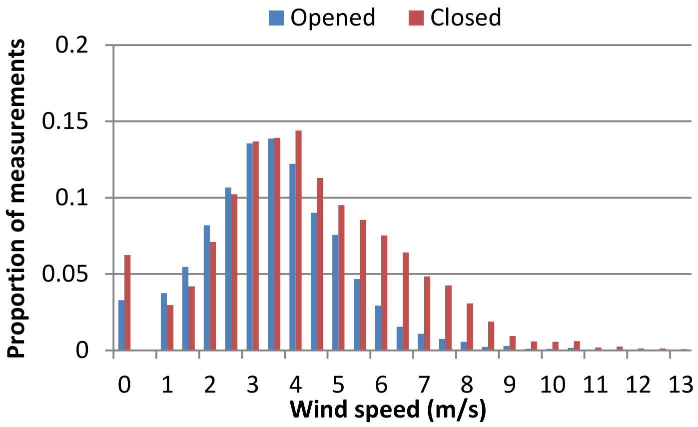


Figure 5-7: Wind speed when windows were open and closed

Daily solar hours were only obtained for Periods 1 and 2. Figure 5-8 presents the histogram distribution for daily solar hours for when windows were open and closed. From the distribution, it can be observed that on sunnier days slightly more windows were opened compared to less sunnier days.

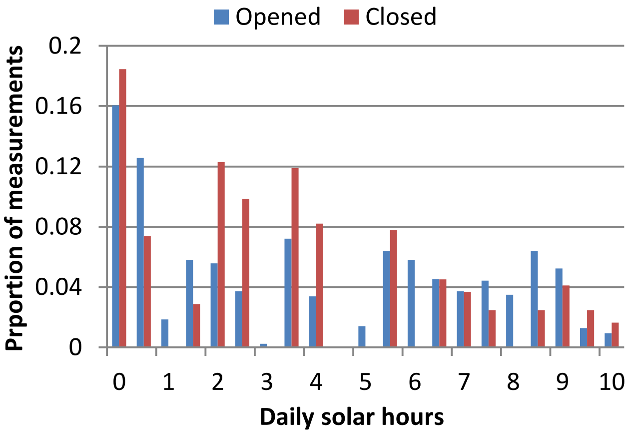


Figure 5-8: Daily solar hours for windows open and windows closed

Hourly average rainfall is presented in Figure 5-9 for when windows were open and when they were closed. Over 80% of the survey period were dry days. The maximum amount of rainfall recorded was 11.8mm/hr but this only occurred for approximately 0.02% of the total rainfall data. During periods of rainfall, the proportions of windows open were slightly lower compared to windows closed.

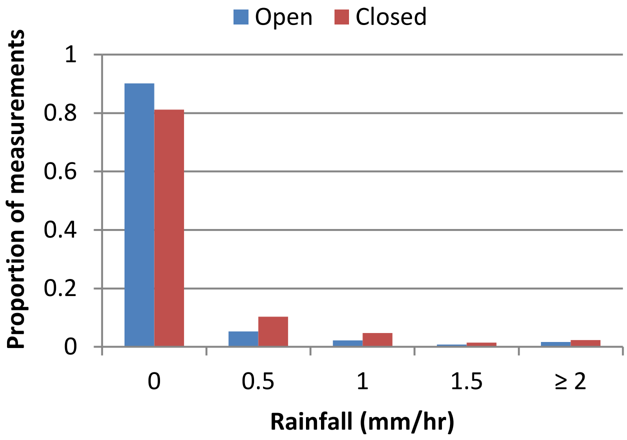


Figure 5-9: Average hourly rainfall for windows open and windows closed

5.4.3 Correlations between environmental variables

Correlations between the environmental variables were assessed to determine if there were any issues with multicollinearity. Table 5-4 presents the correlations between the variables. All correlations with the exception of the ones highlighted in red were significant at a level of 0.01 or 0.05. The values in red were not significant. The calculated correlations show that there are no problems with multicollinearity as none of the correlation is greater than 0.8.

Table 5-4: Correlations between environmental variables

	T_{in}	RH_{in}	T_{out}	RH_{out}	**Rain**	**Wind**	**Solar**	CO_2
T_{in}	-							
RH_{in}	-0.18†	-						
T_{out}	0.36†	0.65†	-					
RH_{out}	-0.28†	0.03†	-0.51†	-				
Rain	0.003	0.02*	-0.04†	0.22†	-			
Wind	0.07†	-0.19†	-0.06†	-0.08†	0.05†	-		
Solar	0.07†	-0.05†	0.02	-0.09†	-0.03*	0.93†	-	
CO_2	0.14†	-0.13†	-0.18†	0.04†	0.003	-0.06†	-0.12†	-

* correlation is significant at the 0.05 level

† correlation is significant at the 0.01 level

5.5 Univariate logistic analysis

In order to assess the relative importance of different variables in influencing window opening initially univariate logistic regression was carried out., The data presented in section 5.5.1 showed that the data for CO_2 concentration, outdoor relative humidity, wind speed and rainfall, are skewed which may provide poor quality regression results. To correct this, natural log transformations were performed in order to improve their distribution. Transformation of rainfall did not improve the distribution and so they were left in their original format. Table 5-5 presents the transformed variables and the format of the transformation. Wind speed was transformed by adding the constant 1 to the data as it contained zero values. The zero values may be because the recorded values were too small or because of measuring accuracy of the weather station instrumentation. Outdoor RH was negatively skewed and so this variable was transformed by reversing the score before taking a log of the value.

Table 5-5: Transformed variables

Variable	**Transformed variable**
CO_2	$\ln(CO_2)$
Wind speed	ln(Wind speed + 1)
Outdoor RH	ln(100 – Outdoor RH + 1)

To determine the link between an environmental parameter and the occurrence of open windows, the observed proportion of open windows corresponding to the measured variables were examined. The probability of a window being in the open state was assessed for each environmental variable. Statistical significance was observed for all of the variables at a statistical level of $p < 0.01$. The regression parameters (see equation 3-1 and 3-2 in section 3.5.1) are presented in Table 5-6 and the resulting curves are presented in the subsequent Figures 5-10 to 5-13.

Table 5-6: Regression parameters from univariate analysis for window opening due to environmental variables

Environmental variables	$\boldsymbol{a}$	$\boldsymbol{b}$
Indoor temperature (T_{in}) (°C)	-4.27 ± 0.14	0.19 ± 0.01
CO_2 concentration (CO_2) (ppm)	9.00 ± 0.32	-1.47 ± 0.05
Indoor relative humidity (RH_{in}) (%)	-2.35 ± 0.07	0.05 ± 0.002
Outdoor temperature (T_{out}) (°C)	-2.51 ± 0.04	0.20 ± 0.003
Outdoor relative humidity (RH_{out}) (%)	-2.53 ± 0.07	0.78 ± 0.02
Wind speed (W_s) (m/s)	0.55 ± 0.04	-0 60 ± 0.03
Wind direction (W_d) (°)	-0.20 ± 0.03	0.0001 ± 0.0001
Rain (R_a) (mm/hr)	-0.26 ± 0.01	-0.27 ± 0.03
Solar hours (S_o) (hr)	1.09 ± 0.11	0.05 ± 0.02

5.5.1 Indoor temperature

Indoor temperature in one of the case study offices was measured to be on average 3.7°C colder than the other offices. Indoor temperatures in the range of 9.8°C and 14.5°C were recorded during the winter season in this office and they made up 0.06% of the indoor temperature dataset. To examine the impact of the recorded range on the regression model, two options were analysed. Option 1 was to include all the recorded indoor temperatures and the Option 2 was to analyse only the data where the minimum temperature was at or above comfortable temperature recommended in the CIBSE standard (CIBSE 2006). The equation used to calculate the lower margin of comfortable temperature was used. This is given in equation 5-1. Using the corresponding monthly mean of outdoor temperature of 3.1°C, the calculated minimum temperature was 17.8°C.

$$T_{comfortable} = 16.8 + T_{mm} \tag{5-1}$$

Where $T_{comfortable}$ is the temperature required for comfortable conditions and T_{mm} monthly mean of outdoor temperature.

The temperature range used in the regression analysis and the resulting regression parameters used to plot the curves are presented in Table 5-7. Figure 5-10 presents the response and the fitted logistic regression curve as a function of the entire indoor temperature range recorded in the current survey (Option 1: 9.8°C to 34.8°C) and for the altered range (Option 2: 18°C to 34.8°C).

The observations and the fitted curves show that the proportion of windows open increased with increasing indoor temperature. There is very little difference between the curves for option 1 and option 2. The regression coefficient calculated for the warmer temperature only is slightly higher than that calculated with all the monitored points. From Figure 5-10 it is clear this makes very little difference to the predicted probabilities.

Table 5-7: Regression parameters for indoor temperature

Indoor temperature	Temperature range	a	b
Option 1	9.8 – 34.8°C	-4.266 ± 0.143	0.181 ± 0.006
Option 2	17.8 – 34.8°C	-4.650 ± 0.147	0.198 ± 0.007

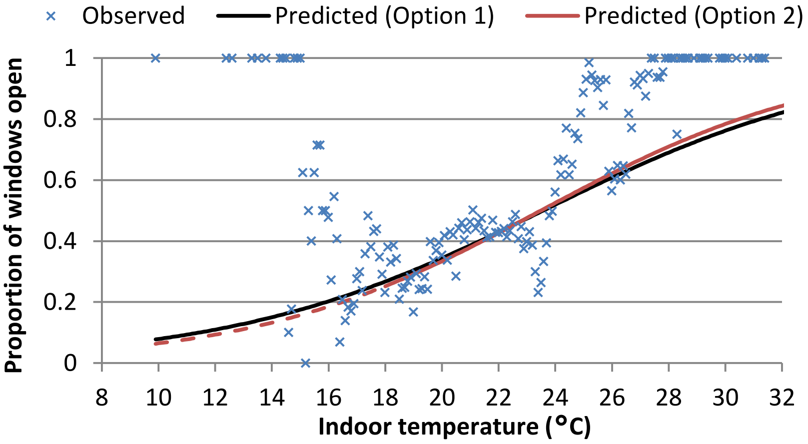


Figure 5-10: Observed and fitted logistic regression curve showing the predicted probability for windows open as a function of indoor temperature for Options 1 and 2

5.5.2 Outdoor temperature

The observed proportion of windows open as a function of outdoor temperature and the resulting logit distribution is presented in Figure 5-11. Outdoor temperature was also positively correlated with the proportion of windows open and the regression curve is a much better fit of the observed data compared to the curve for the indoor temperature observed data. This implies that outdoor temperature may be a better predictor for windows open. This pattern has also being observed and reported by several researchers in previous studies (Herkel *et al.* 2008; Haldi & Robinson 2009).

The regression curve from the current study predicts the highest proportion of windows open when outdoor temperatures are greater than 8°C. For both indoor and outdoor temperatures, proportion of windows open increased until it reached the maximum. There was no observable decrease after a certain temperature was reached, which is what Haldi and Robinson (2009) observed for both indoor and outdoor temperatures and Rijal (2008) also observed for outdoor temperature.

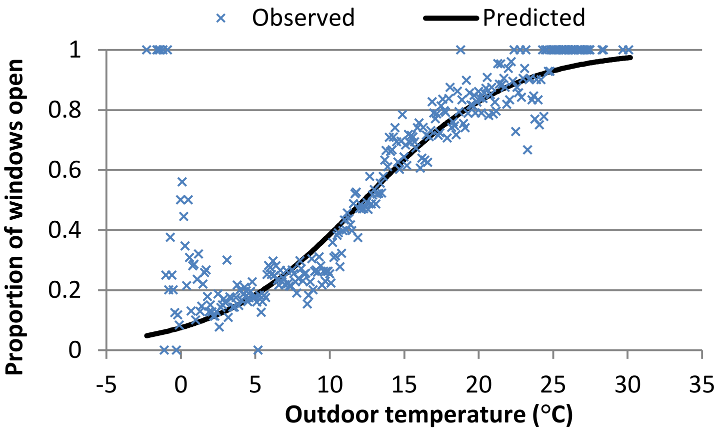


Figure 5-11: Observed and fitted logistic regression curve showing the predicted probability for windows open as a function of outdoor temperature

5.5.3 CO_2 concentration

For the observed CO_2 data, lower CO_2 concentrations were recorded when the windows were open. This makes sense as ventilation rates through the indoor space increase when windows are opened, resulting in a decrease in CO_2 concentration. It could be that other parameters influence window use which in turn causes a decrease in CO_2 concentration. However, this observation and resulting regression curve does not give any indication if CO_2 influences window opening. This will be explored in the analysis of window state changing events in Section 5.6. Figure 5-12 presents the observed proportion of windows open as a function of CO_2 concentration and the resulting regression curve from the observed data.

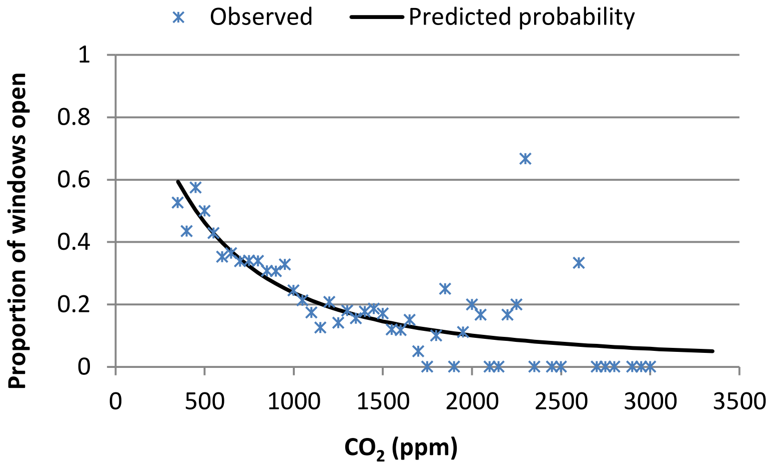


Figure 5-12: Observed and fitted logistic regression curve showing the predicted probability for windows open as a function of CO_2 concentration

5.5.4 Other environmental variables

The observed proportions of windows open as a function of indoor and outdoor relative humidity, rainfall, wind speed and direction and mean daily solar hours are presented in Figure 5-13(A)-(F). The pattern observed for indoor relative humidity was very much similar to indoor temperature. Proportion of windows open increases from approximately 35% relative humidity until it reaches maximum. On the contrary, a decrease in the proportion windows open is observed for increasing outdoor relative humidity. Similar to outdoor relative humidity, an increase in mean hourly rainfall and mean wind speed are associated with a decrease in the proportions of windows open. However, the model for rainfall is a poor fit of the observed data. For rainfall, the initial observation shows quite large variations in proportion of windows open, particularly for rainfall levels greater than 2mm. This suggests that rainfall may not be a good descriptor of the proportion of window open state observed. The curve for wind speed is less sharp compared to the temperature and relative humidity curves. No clear variation was found between wind direction and proportion of windows open. The influence of wind direction was negligible (regression coefficient, $b_{Wd} = 0.0001 \pm 0.0001$). The scatter plot of the observed data for daily solar hours shows no clear pattern or no clear association with the observed proportion of windows open. The fitted regression curve shows only a slight increase in proportion of windows open with increasing daily solar hours.

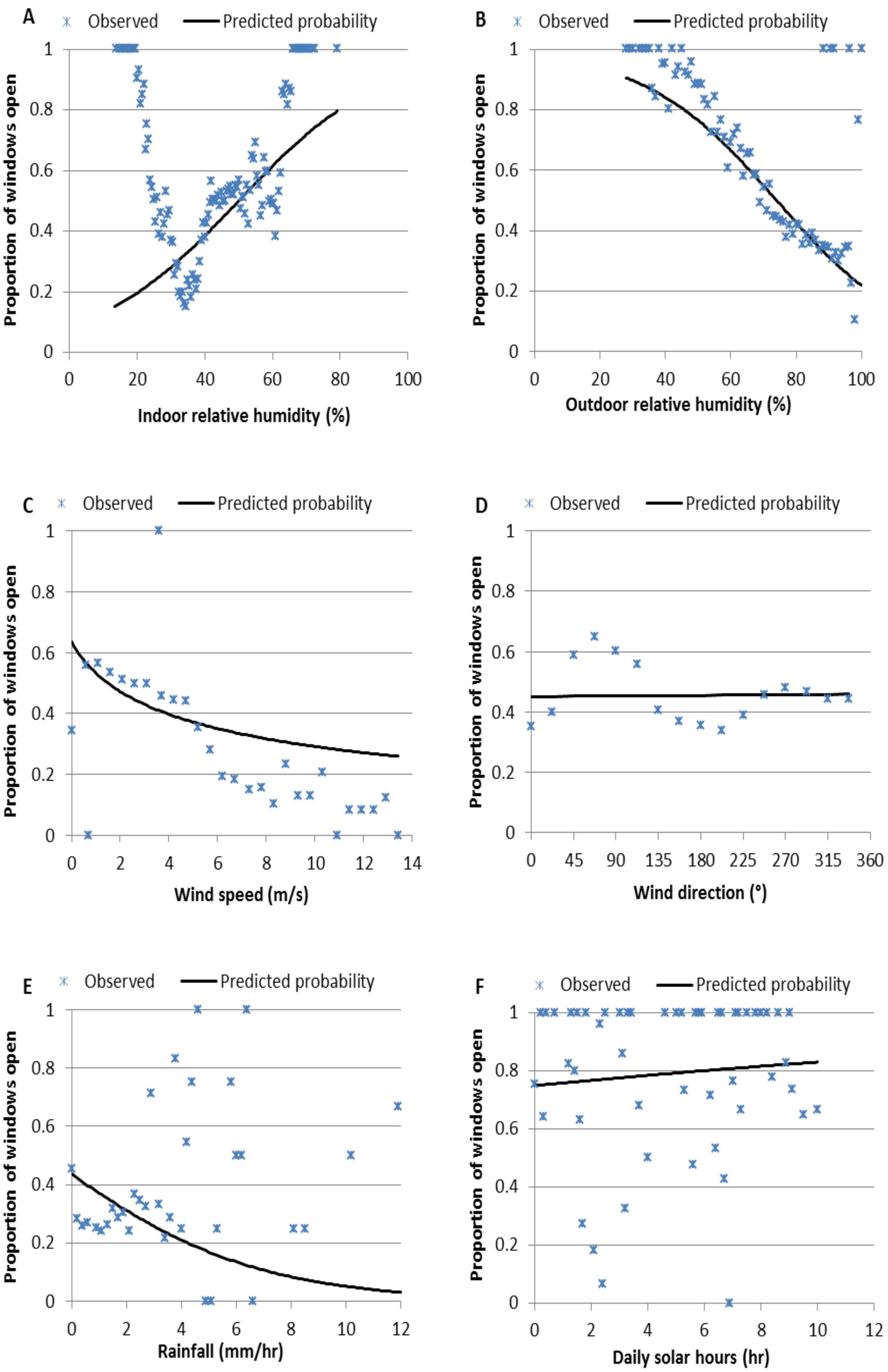


Figure 5-13: Observed and fitted logistic regression curve showing the predicted probabilities for windows open as a function of environmental parameters (A)-(F)

The above univariate analysis shows how the measured environmental variables relate to the observed proportions of windows in the open state. One advantage of the indoor survey is that due to the continuous measurement of environmental variables and window state, the factors that occur just before a window changes state can be used to investigate which factors significantly predict window opening. A variation in window use at different times periods was observed in the photographic survey and this has also been reported in previous studies (Yun & Steemers 2008; Herkel *et al.* 2008; Haldi & Robinson 2009). In the previous studies, the working day was divided into three time periods – arrival, intermittent and departure. From the current indoor survey, the influence of the measured environmental variables on window opening was investigated for these time periods. This analysis will provide a more detailed assessment of what makes occupants open windows at the different times in the day. The following sections present how the time periods were identified and the results from the time dependent analysis conducted.

5.6 Window state changing events

During the survey period, the occupied time in the case study offices was divided into three occupancy periods – arrival, intermittent and departure periods. Since there are no set working hours for the occupants in these buildings, entry and departure information was obtained from state loggers mounted on the door during the monitoring period. The period between first entry and last departure was described as *intermittent hours* as defined by Yun and Steemers (2008). During the intermittent period, the window can be opened and closed repeatedly. Figure 5-14 is a typical day in one of case study offices, showing periods when the window was opened, times when the door was opened and the indoor environmental conditions measured. Figure 5-15 shows an example of how occupancy periods were identified. For instance, if the office occupant arrives at 09:23, the five minutes after the door opening was classed as the arrival period (09:23 - 09:28) and any window state changing event within this period were classed as events on arrival. The five minute period before last departure was classed as departure period (17:48 - 17:53 in this example) and window state changing that occurred within this period were event on departure. The period between arrival and departure was the intermittent period (09:28 - 17:48) and events in this period were events during the intermittent period. For each office, an initial door opening was recorded between 06:30 and 07:30. The time between this initial opening (indicating entry) and the next opening (indicating departure) was on average 20 seconds. It is assumed that this initial entry and departure from the office was by the cleaner, possible to empty the bin. From Figure 5-14, it can be seen that door opening occurred during the intermittent period. Data from the state logger mounted on the door showed state duration and so it could be determined whether the door had been opened only for entry/exit or if it had been left ajar.

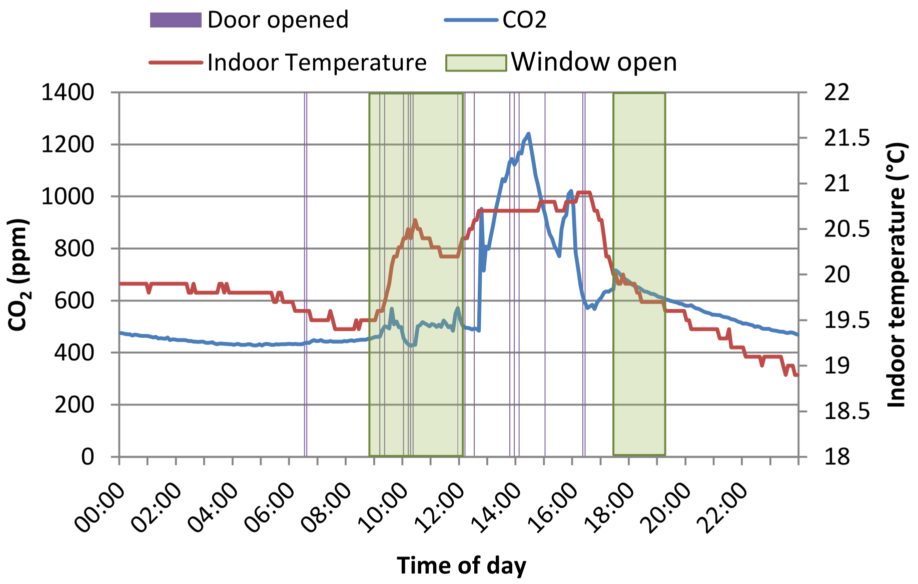


Figure 5-14: A typical day in a case study office showing times of door and window opening

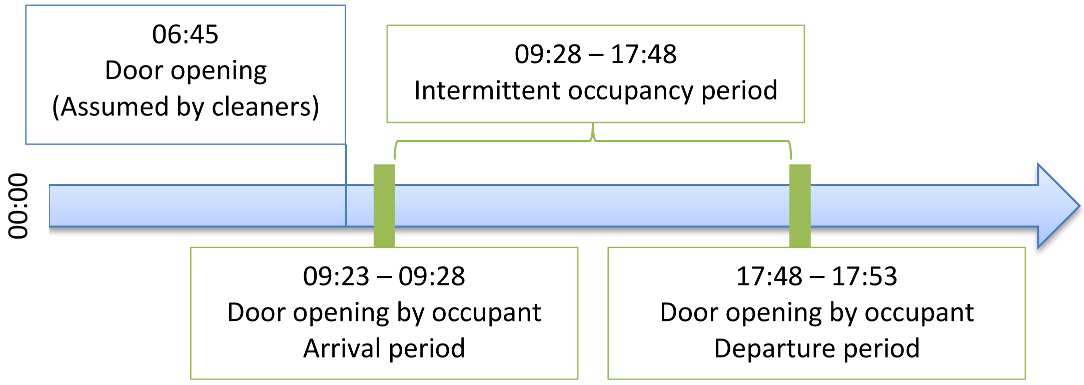


Figure 5-15: Example timeline indicating the three periods: Arrival, Intermittent, and Departure. The exact times will vary for each office and day.

During the survey period, a total of 726 window interventions were recorded. From this, 21% occurred during the arrival period, 62% occurred during the intermittent occupancy hours and 16% occurred during departure from the office. For 55% of all arrivals, a window changed state and for 48% of all departures, a window changed state. For the remainder of arrivals and departures, windows stayed either open or closed. As shown in Table 5-8, there was a difference between window use behaviour on first entry and during the intermittent period. Most window opening occurred on first entry and most window closing occurred at last departure from the office. There were times when windows stayed in the same state on arrival and at departure. During the intermittent period, the difference between the proportions of windows changing from closed to open and from opened to close was significantly less than that recorded at entry and at departure.

Table 5-8: Window changing state events during occupancy

Occupied period	**Closed to open**	**Opened to close**
Arrival period	76%	24%
Intermittent period	46%	54%
Departure period	23%	77%

5.6.1 Window opening events

Logistic regression was used to determine the environmental variable(s) that influenced the change in a window state from closed to open and to describe the probability of window opening due to the influence of these environmental parameters. For this analysis, environmental parameters immediately preceding the opening action of the window were considered and these were used in the regression analysis to infer window opening models. A period of 5 minutes prior to the window opening event was used. Overall, average indoor temperature was 1.5°C higher when a window changed from closed to open than from opened to close. CO_2 concentration was also marginally higher when a window changed from closed to open compared to a change from opened to close (134ppm). For each occupancy period, indoor temperature just before a window opening intervention was slightly higher than when a window was closed. Particularly on arrival, the average indoor temperature just before window opening was 3.1°C higher than when a window changed from opened to close. Maximum average CO_2 concentrations were recorded when windows state changed from closed to open during intermittent hours and at departure. Outdoor temperature just before window opening was only 0.5°C higher than just before window closing and for wind speed, the difference was negligible. Average indoor and outdoor environmental conditions occurring just before a window intervention for each occupied period are presented in Table 5-9.

Table 5-9: Descriptive statistics for environmental variables before window changing state events

		T_{in} (°C)	CO_2 (ppm)	RH_{in} (%)	T_{out} (°C)	RH_{out} (%)	W_s (m/s)	R_a (mm/hr)	S_o (hr)
Arrival									
Closed to open	Min	19.0	381	15	-2.4	63	0	0	0
	Max	26.2	1342	57	20.0	98	13.4	2.7	8.1
	Ave	22.4	551	39	7.3	84	3.7	0.086	2.5
	S.D.	1.2	150	8.8	4.8	9.3	2.3	0.33	2.8
Opened to close	Min	14.8	358	33	4.4	60	0	0	0
	Max	23.1	1119	60	16.3	96	7.2	0.2	9.4
	Ave	19.3	517	43	9.7	79	3.5	0.006	3.9
	S.D.	2.3	145	7.7	3.6	9.8	1.8	0.034	3.9
Intermittent									
Closed to open	Min	17.5	368	25	-0.3	44	0	0	0
	Max	26.8	3353	64	23.8	97	10.3	3.4	9.9
	Ave	22.7	943	41	10	75	4.1	0.092	3.6
	S.D.	1.3	425	7.8	5.0	11.8	1.9	0.34	2.8
Opened to close	Min	15.6	358	21	-0.1	48	0	0	0
	Max	26.9	2578	60	24	98	13.4	8.4	9.4
	Ave	22.2	775	40	9.8	75	4.3	0.16	3.6
	S.D.	1.7	357	8.6	5.1	11.4	2.0	0.69	3.0
Departure									
Closed to open	Min	20.4	398	26	4.1	54	0.51	0	0
	Max	25.2	1652	55	23.7	97	10.3	1.0	9
	Ave	23.3	922	41	11.8	79	3.99	0.103	3.4
	S.D.	1.2	359	7.1	4.6	11	2.1	0.243	3.6
Opened to close	Min	15.9	370	21	0	49	0	0	0
	Max	24.8	1626	64	19.3	97	13.4	4.2	8.8
	Ave	22.5	723	37	8.1	80	3.9	0.19	3.2
	S.D.	1.7	259	8.9	4.7	9.8	2.4	0.59	3.1

5.7 Time dependent analysis

The time dependent models were determined by carrying out separate logistic regression analyses for window opening events during the arrival, intermittent and departure periods. From the results, indoor temperature is consistently significant, implying that it has an influence on window opening during all three periods. This can be seen in Tables 5-10, 5-13and 5-15. CO_2 concentration is significant during intermittent and departure periods but not on arrival and outdoor temperature is only significant on arrival and at departure.

Following on from the univariate models, models with multiple variables were considered. The significance statistic test and the goodness-of-fit measures were used to select the variable that best described the observations made in the study.

5.7.1 Events during arrival period

Window interventions included in this analysis are those that occurred on first arrival into the office as determined by the door state monitors. During the monitoring period, for 36.4% of arrival events, windows changed from closed to open and for 11.4%, windows changed from open to closed. For the remainder of arrival events, windows remained in the state they had been left in on the previous departure. In a univariate analysis, variables that were found to influence window opening on arrival were indoor and outdoor temperatures and indoor and outdoor relative humidities. The regression parameters for window opening on arrival are presented in Table 5-10. The p-values highlighted in green represent the variables which were found to be significant. The correlation between outdoor temperature and indoor relative humidity was strong and significant ($r = 0.831$, $p < 0.001$) and the VIF for outdoor temperature and indoor relative humidity were 10.5 and 8.7 respectively indicating that the standards errors would be 3.2 and 2.9 times higher respectively than if they were not correlated. Due to humans intuitive response to temperature and also because a wider range of relative humidity can be tolerated particularly when sweating is not an issue, indoor relative humidity was excluded from the multivariate analysis and the contribution of outdoor temperature was assessed. There were no strong correlations between the other variables.

Table 5-10: Regression parameters for environmental variables used to infer window opening during arrival period

Variables	a	b	p
T_{in}	-21.24 ± 3.92	1.07 ± 0.19	0.000
CO_2	-7.78 ± 6.74	1.47 ± 1.08	0.173
RH_{in}	3.99 ± 1.05	-0.06 ± 0.02	0.008
T_{out}	2.34 ± 0.46	-0.12 ± 0.05	0.010
RH_{out}	3.71 ± 1.10	-0.83 ± 0.37	0.024
W_s	1.20 ± 0.58	0.11 ± 0.39	0.779
W_D	1.47 ± 0.50	-0.001 ± 0.002	0.799
R_a	1.23 ± 0.20	6.15 ± 4.82	0.202
S_o	2.32 ± 0.83	-0.15 ± 0.17	0.369

The model fitting information presented in Table 5-11 shows that window opening events on arrival was better explained by indoor and outdoor temperature. The p-value highlighted in red shows the non-significant variable.

Table 5-11: Model fitting information for variables influencing window opening during arrival period

Model	**Likelihood ratio**	p	**Akaike information criterion**	**Nagelkerke's R^2**
T_{in}	13.6	0.000	211	0.067
T_{out}	6.1	0.015	268	0.030
RH_{out}	1.2	0.271	122	0.006

In the multivariate analysis, the addition of indoor temperature gave the lowest AIC value and the highest likelihood ratio statistic. Outdoor temperature was also significant but with a lower LR value and higher AIC compared to indoor temperature. Outdoor relative humidity was no longer a significant variable in the arrival only analysis. The calculated Nagelkerke R^2 for outdoor relative humidity showed that it only explains 0.6% of the variation in window opening on arrival. Indoor and outdoor temperatures were therefore maintained in the final model and the goodness-of-fit measure was increased from 0.067 (indoor temperature alone) to 0.091 (indoor and outdoor temperature). The regression parameters are presented in Table 5-12. From the analysis conducted in the present study, window state changing from closed to open during arrival periods is governed by indoor and outdoor temperatures and can be expressed by equation 5-2. According to Nagelkerke's R^2, a combination of these two variables explains 9.1% of the variance in window opening on arrival.

Table 5-12: Regression parameters for window opening on arrival

Regression parameters	**Estimate**	p	**Nagelkerke's R^2**
a	-20.28 ± 3.97		
Indoor temperature (b_{Tin})	1.11 ± 0.20	0.000	0.067
Outdoor temperature (b_{Tout})	-0.20 ± 0.08	0.010	0.5970.091

$$log\left(\frac{p}{1-p}\right) = -20.28 + 1.11T_{in} - 0.20T_{out} \tag{5-2}$$

The interesting observation here is that even though outdoor temperature is a significant variable in the model, the negative coefficient implies that the lower the outdoor temperature, the more likely an occupant is to open a window on arrival. This is in contrast to the observations of proportion of windows open as a function of outdoor temperature and also in contrast to results from Haldi and Robinson (2009) who found that both indoor and outdoor temperatures were positively associated with window opening on arrival. Yun and Steemers (2008) in their time dependent analysis of windows opening did not find outdoor temperature to be a significant factor influencing window opening on arrival. Even with the establishment of indoor and outdoor thermal conditions as the main drivers influencing window opening, there is still no consensus on the contribution of outdoor temperature as a factor influencing window opening. The results obtained in the current analysis offers a different point view for the role of outdoor temperature on window opening on arrival. A possible explanation for the negative impact of outdoor temperature could be that thermal history and transition between environments with different thermal conditions may have an effect on window opening behaviour. For occupants coming in from outdoors, due to the sudden transition in environments they feel warmer and respond to it. This impact of transition will however be dependent on a number of factors including the time of exposure, the degree of change, the direction of the thermal change (neutral to warm or neutral to cool or vice versa) and the previous activity conducted by the occupant.

Parkinson *et al.* (2012) conducted a pilot study to investigate the relationship between core and skin temperatures and thermal pleasure in transient thermal environments. In their experiment, the subjects were transitioned from a sedentary, neutral environment into a warmer or cooler environment or from an increased metabolic activity to a warmer or cooler environment. Participants were also asked to rate their thermal sensation, preference and pleasure after each transition. From their results they showed that a step change in temperatures can result in thermal displeasure but this depends on the internal thermal state of the subject. One example given to illustrate this observation is that in the heating season when we rush to arrive at a place on time, the dry air from the heating will feel unpleasant due to the metabolic heat gain. Adaptation measures, such as opening a window where possible or adjusting clothes level will help to restore our thermal pleasure.

Kaynakli and Kilic (2005) had also shown earlier that when an occupant enters into a space with a higher temperature, the body temperature increases and the insulation provided by clothing may have a reducing effect on heat loss from the body and an increasing effect on skin temperature. These will result in thermal discomfort and adaptive measures such as adjusting clothes level (e.g. taking of a coat) or opening a window to increase air flow may help to restore thermal comfort. Preliminary work has shown that temperature changes of 1°C and 2°C do not significantly affect people's thermal perception. However, differences in temperature of 4°C or more is significant or when the direction of the change is from the extreme towards a moderate temperature (Vargas & Stevenson 2014).

In the indoor survey conducted for this thesis, participant's activity just before arrival, e.g., walking or cycling to work, would have an impact on their window opening behaviour. And in the winter, due to heating provision, the indoor temperature would be significantly higher than the outdoor temperature. These could be the reasonable explanations for the negative correlation between window opening and outdoor temperature in the colder season.

Direct solar gain may be beneficial as it can be retained for heating an indoor space. Indoor temperatures can increase due to high solar gains. High solar gains can result in high indoor temperature, increasing the difference between indoor and outdoor temperature. During times of high solar gain, an occupant may open a window to cool the room in order to improve their thermal comfort. Since only daily solar hours is recorded at the weather station described in Chapter 3, for the survey conducted for this thesis, it was not possible to investigate the impact of solar gain as there was no information on solar radiation. However it is clear that solar gain is another factor to be considered when investigating window opening behaviour and studies conducted in residential buildings have shown that window opening is positively correlated with solar radiation as well as indoor temperature

(Andersen *et al.* 2013). If this is the case the response may be to the relationship between indoor and outdoor temperatures. This observation may also vary between seasons and so a seasonal analysis was conducted in Section 5.8.

5.7.2 Events during intermittent period

During intermittent periods, environmental parameters just before a window intervention were used to infer window opening models. For periods where there were no interventions, the environmental parameters were averaged over one hour intervals. For the intermittent period, 5.5% of windows changed from closed to open, 6.4% changed from opened to close and 88% remained in the same state as from arrival (47.1% remained opened and 40.9% remained closed). This shows that actions on windows are quite rare, with window opening even slightly less than window closing. The influence of indoor temperature and CO_2 concentration were assessed as they were the only significant variables from the univariate analysis, shown in Table 5-13. For this time period, outdoor temperature was not found to be a significant variable ($p = 0.640$, $R^2 = 0.001$). This result is consistent with the findings of Yun and Steemers (2008) but in contrast to that of Haldi and Robinson (2008). However, in the latter study, the main driving variable for window opening during intermittent occupancy period was indoor temperature.

In the present multivariate analysis, the reduced AIC and the increased likelihood ratio statistic of CO_2 concentration showed that this variable offered the best fit for the model describing window opening during the intermittent period. Indoor temperature was also a significant variable in the final model. The statistical tests performed on the significant variables showed that indoor temperature explained 4.2% of the variation and CO_2 concentration explained 7.9%. In the multivariate model, 9.5% of the variation in windows changing state from closed to open was explained by a combination of indoor temperature and CO_2 concentration. The regression parameters and the goodness-of-fit information for each parameter are presented in Tables 5-13 and 5-14.

Table 5-13: Regression parameters for environmental variables used to infer window opening during intermittent period

Variables	$\boldsymbol{a}$	$\boldsymbol{b}$	$\boldsymbol{p}$
T_{in}	-5.58 ± 1.50	0.24 ± 0.07	0.000
CO_2	-8.76 ± 1.77	1.30 ± 0.27	0.000
RH_{in}	-0.77 ± 0.47	0.02 ± 0.01	0.180
T_{out}	-0.24 ± 0.21	0.01 ± 0.02	0.640
RH_{out}	-0.36 ± 0.52	0.07 ± 0.17	0.696
W_s	0.03 ± 0.39	-0.12 ± 0.24	0.620
W_D	-0.03 ± 0.24	-0.001 ± 0.001	0.556
R_a	-0.13 ± 0.10	-0.26 ± 0.22	0.237
S_o	-0.30 ± 0.30	0.01 ± 0.07	0.859

Table 5-14: Model fitting information and regression parameters for variables influencing window opening during intermittent period

Regression parameters		$\boldsymbol{p}$	**Likelihood ratio**	**Akaike information criterion**	**Nagelkerke's** $\boldsymbol{R^2}$
a	-11.28 ± 2.13				
T_{in}	0.16 ± 0.07	0.020	6.9	341	0.042
CO_2	1.13 ± 0.27	0.000	8.3	120	0.079

The coefficients indicate that during intermittent occupancy periods, as indoor temperature and indoor CO$_2$ concentration increases, occupants are more likely to open a window. The predicted probability of windows changing from closed to open is given by equation 5-3.

$$log\left(\frac{p}{p-1}\right) = -11.28 + 0.16T_{in} + 1.13\ln CO_2 \tag{5-3}$$

The intermittent occupancy period results show that CO$_2$ concentration predicts window opening. At lower or more comfortable indoor temperatures, the predicted probabilities of a window opening are lower for a given CO$_2$ concentration compared to a higher indoor temperature at the same CO$_2$ level. For instance when the CO$_2$ concentration is 1500ppm in an office where indoor temperature is 18°C, the probability of window opening is 0.47. At the same CO$_2$ level in 20°C and 28°C, the predicted probabilities increase to 0.55 and 0.82 respectively. This implies that in thermally comfortable environments, occupants are less likely to open a window even though CO_2 concentration has a significant influence on window opening and indoor temperature may act as a suppressor variable. Figure 5-16 gives an indication of the variation in probabilities of window opening due to CO_2 concentrations and at different indoor temperatures.

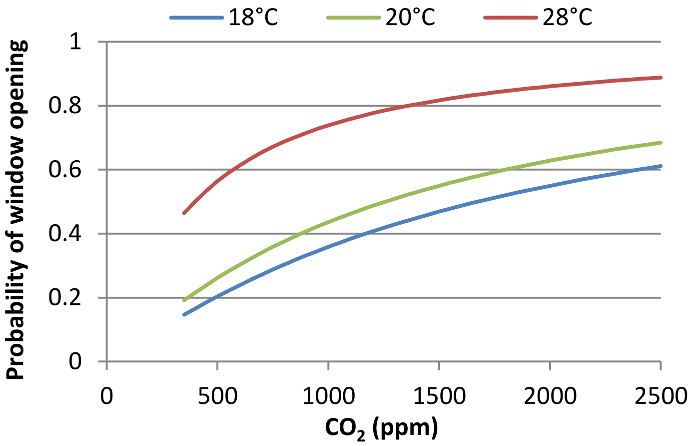


Figure 5-16: Probability of window opening due to CO_2 concentration at different indoor temperatures during the intermittent period

5.7.3 Events during departure period

Window interventions included in this analysis are those that occurred on last departure as determined by the time of the last door closing in the day. During the monitoring period, for 12% of departure events, windows changed from closed to open and for 36%, windows changed from opened to closed. For the remainder of the departure events, 21% of windows remained either opened indicating the use of night ventilation. As explained by Haldi and Robinson (2008), window interventions on departure are of a different nature and they are not to modify the indoor environment for immediate further occupancy. In buildings with night ventilation, occupants may open a closed window on departure mainly to induce night ventilation and depending on the design of the building façade, security and elements of the weather such as rain may not be an issue affecting window use behaviour.

In the current analysis, indoor temperature, CO_2 concentration and outdoor temperature were the significant variables associated with window opening. Table 5-15 presents the regression parameters for all the variables included in the analysis. Indoor relative humidity and outdoor temperature were significantly correlated $(r = 0.816,\ p < 0.001)$. The calculated VIF for outdoor temperature was low $(VIF = 3)$ however, even at this value the standard error for outdoor temperature will be almost double (1.7) compared to what it would be if there was no correlation between these variables.

Table 5-15: Regression parameters for environmental variables used to infer window opening during departure period

Variables	$\boldsymbol{a}$	$\boldsymbol{b}$	$\boldsymbol{p}$
T_{in}	-11.27 ± 4.39	0.44 ± 0.19	0.020
CO_2	-12.51 ± 4.13	1.72 ± 0.62	0.005
RH_{in}	-3.25 ± 1.04	0.05 ± 0.03	0.032
T_{out}	-2.63 ± 0.54	0.15 ± 0.05	0.001
RH_{out}	-1.56 ± 1.24	0.14 ± 0.41	0.729
W_s	-1.53 ± 0.67	0.27 ± 0.04	0.526
W_D	-1.39 ± 0.54	0.001 ± 0.002	0.606
R_a	-1.07 ± 0.23	-0.46 ± 0.60	0.451
S_o	-0.77 ± 0.63	0.02 ± 0.14	0.867

In the multivariate analysis, indoor temperature was no longer a significant variable in the model ($p = 0.059$). The statistical tests performed on the remaining two significant variables showed that outdoor temperature explained the variation in window opening on 14.3% of the variation in window opening during the departure period. Carbon dioxide explained 10.1% of the variation. In the multivariate model, 28.8% variation in window opening was explained the combination of outdoor temperature and CO_2 concentration. Table 5-16 presents the regression parameters for the variables that significantly influenced windows opening during the departure period. The positive regression coefficients for outdoor temperature and CO_2 concentration indicate that as these conditions increase, the probability of windows changing from closed to open on departure also increases.

Table 5-16: Regression parameters for window opening on departure (outdoor temperature and CO_2 concentration)

Regression parameter	**Estimate**	$\boldsymbol{p}$	**Nagelkerke's $\boldsymbol{R^2}$**
a	-18.9 ± 4.86		
Outdoor temperature (b_{Tout})	0.20 ± 0.05	0.000	0.143
Carbon dioxide concentration (b_{CO2})	2.39 ± 0.69	0.001	0.101

As mentioned previously, window opening on departure is not to modify the indoor environments for immediate occupancy (for example to improve thermal comfort or to improve air quality). Even though CO_2 concentration was found to be significant variable, it should be treated with caution because higher levels of CO_2 concentrations can be recorded when windows are closed during occupied times (i.e. reduced ventilation when windows are closed) and the concentration may be due to the fact that CO_2 levels will be higher at the end of the day. This is another instance of when the window closed state affects the variable that is used as the predictor of the action on windows.

In the multivariate analysis, an association between indoor temperature and window opening was not achieved as indoor temperature just missed out on significance. From the measured indoor conditions during the departure periods, a small correlation was observed between indoor temperature and CO_2 concentration ($r = 0.184$, $p = 0.05$). An alternative analysis was conducted with indoor and outdoor temperatures as the variables to compare the contribution of indoor temperature with that of CO_2 concentration. Results from this analysis showed that indoor temperature was significant variable when added to the model with outdoor temperature alone. The Nagelkerke R^2 however showed that the model with outdoor temperature and CO_2 concentration explained a higher proportion of the variation in window opening than the model with outdoor and indoor temperatures. In the alternative multivariate model, 21.2% variation in window opening was explained the combination of outdoor and indoor temperature as opposed to the 28.8% explained by outdoor temperature and CO_2 concentration. Table 5-17 presents the regression parameters for the model with outdoor and indoor temperatures.

Table 5-17: Regression parameters for window opening on departure (outdoor and indoor temperatures)

Regression parameters	**Estimate**	p	**Nagelkerke's** R^2
a	-12.8 ± 4.61		
Outdoor temperature (b_{Tout})	0.15 ± 0.05	0.000	0.143
Indoor temperature (b_{Tin})	0.45 ± 0.20	0.024	0.085

From the results of the current analysis, the model, the predicted probability of windows changing from closed to open is given on departure can be expressed by equation 5-4.

$$log\left(\frac{p}{1-p}\right) = -18.9 + 0.20T_{out} + 2.39 \ln CO_2 \tag{5-4}$$

5.8 Season specific window opening

Observations made in the photographic survey showed a variation in windows open due to seasonal changes and time of day. The seasonal variation in window opening behaviour was also observed by *Herkel et al.* (2008). The proportion of windows open was highest in the summer followed by the autumn and it was lowest in the winter. This is expected as outdoor temperatures are highest in the summer and lowest in the winter. The time of day analysis gave interesting insights into the role of the significant parameters on window opening, particular the nature of the role of outdoor temperature during the arrival period. Since there are seasonal variations in occupant window opening behaviour, a time of day analysis in each season may also give a more detailed picture of the role of the predictors. The limitation in carrying out a time of day analysis for the three seasons is that the data set used in the analysis is smaller than if only a time of day or a season-specific analysis is conducted. For assessing variables that significantly predict window opening at different times in different seasons, the data is divided into the seasons they were measured (summer, autumn and winter) in and then into the corresponding time of day (on arrival, during intermittent period and at departure).

From the indoor survey observations, an in-depth analysis was carried out for the arrival and intermittent periods in the three seasons. In the case of the departure, no window openings were recorded during the autumn and the winter season. Once a window had been opened or closed during the previous periods, they remained in the same state on departure. Hence no further regression analysis was carried out for the departure period.

5.8.1 Season specific window opening on arrival

For the arrival period, in all three seasons, the percentage of window states that changed from closed to open was greater that the states that changed from opened to close. Table 5-18 presents the percentages of window state changing events for all three seasons. The percentage of window opening was greatest in the autumn compared to the summer and the winter.

Table 5-18: The proportion of window state changing events on arrival in summer, autumn and winter

Season	Opened to close	Closed to open	No change
Summer	8.1%	17.4%	74.4%
Autumn	19.5%	57.6%	22.9%
Winter	4.3%	26.9%	68.8%

In the regression analysis, the effects of indoor temperature and outdoor temperature and indoor and outdoor relative humidity were considered. These were the significant predictors found in the time of day analysis presented in Table 5-10. The significant predictors of window opening on arrival for each season are shown in Table 5-19.

Table 5-19: Significant predictors of window opening on arrival for summer, autumn and winter

Arrival predictors	Summer	Autumn	Winter
Indoor temperature	✓		✓
Outdoor temperature	✓	✓	✓
Indoor relative humidity		✓	✓
Outdoor relative humidity			✓

In the summer, indoor temperature and outdoor temperature were the significant predictors of window opening. In the model, the probability of window state changing from closed to open increases with increasing indoor and outdoor temperatures. Outdoor temperature was the better predictor as it explained 17.2% of the total variance in the observation. Indoor temperature explained 5% of the variance.

In the autumn, outdoor temperature and indoor relative humidity were the significant predictors of window opening. The observation was however different from that made in the summer. The correlation between outdoor temperature and indoor temperature was however strong and significant ($r = 0.704,\ n = 118,\ p < 0.01$). Considering outdoor temperature alone, the probability of window opening increased with decreasing outdoor temperature. Outdoor temperature explained 10.4% of the variance in the observation. The maximum proportion of window opening occurred in this season (57.6%) even though outdoor temperatures were decreasing. The mean outdoor temperature during arrival period was 8.6°C. This observation suggests that thermal history may influence window opening. In the transition from summer and autumn, occupants' thermal preference may be based on the thermal conditions experienced previously and this may have an impact on their adaptive actions. The adaptive thermal comfort model is based on this idea and seems to be applicable here.

In the winter, indoor and outdoor temperatures and indoor and outdoor relative humidities were significant predictors of window opening. Similar to the autumn observations, correlations between outdoor temperature and both indoor and outdoor humidity were significant and correlation between indoor temperature and indoor relative humidity was also significant. There was no significant correlation between indoor and outdoor temperatures however and an investigation of the data highlighted a tendency for relatively high internal temperatures in the winter which may affect this analysis. The average indoor temperature measured during the winter survey periods was 23.5°C. This average measurement made up 27.4% of the winter indoor temperature data set. For free-running buildings the recommended indoor comfort temperature for the winter season is from 21°C to 23°C. This range of temperature was recorded in 25.8% of the winter survey period. As expected, the difference between the outdoor and the indoor temperatures is highest in the winter. The outdoor temperature ranged from -2.4°C to 10.7°C and the mean difference between the indoor temperature and outdoor temperature was 19.2°C. Occupants coming into their office from outside may have experienced a sudden sharp increase in temperature and opened a window regardless of the outdoor temperature. In this case, window opening may be due to perceived environment and not the actual physical environment. This could explain the negative correlation where a decrease in temperature outside leads to an increase in window opening probability. Table 5-20 presents the regression parameters for window opening on arrival for each season. All predictors were significant at $p < 0.05$.

Table 5-20: Regression parameters for window opening on arrival in the summer, autumn and winter seasons

Season	**Environmental variable**	$\boldsymbol{a}$	$\boldsymbol{b}$	**Nagelkerke's $\boldsymbol{R^2}$**
Summer	Indoor temperature	-2.31 ± 8.33	0.097 ± 0.37	0.050
	Outdoor temperature	-5.23 ± 3.59	0.33 ± 0.23	0.172
Autumn	Outdoor temperature	3.22 ± 0.87	-0.17 ± 0.08	0.104
Winter	Indoor temperature	10.97 ± 4.34	0.45 ± 0.19	0.121
	Outdoor temperature	1.24 ± 0.37	-0.16 ± 0.08	0.089

The season-specific window opening on arrival has shown that the role of outdoor temperature varies due to seasonal changes. Factors such as thermal history or transition between environments and perceived environment may have an impact on window opening on arrival. This is particularly important for the autumn and winter seasons. In the winter, having the indoor temperature controlled by the heating system may also have an impact on window opening. Sudden transitions between the indoor and outdoor environments when the difference in temperatures is relatively high may cause occupants to open windows regardless of the outdoor thermal conditions.

5.8.2 Season specific window opening during the intermittent period

For the intermittent period, the proportions of window state changing from closed to open ranged from 6.7% in the winter to 4.4% in the summer. Table 5-21 presents the percentages of window state changing events during the intermittent period for each season.

Table 5-21: The proportion of window state changing events during the intermittent period in summer, autumn and winter

Season	Opened to close	Closed to open	No change
Summer	4.7%	4.4%	90.9%
Autumn	8.8%	5.3%	85.9%
Winter	5.5%	6.7%	87.8%

In the regression analysis, the effects of indoor temperature and CO_2 concentration were considered. These were the significant predictors found in the time of day analysis presented in Table 5-13. The significant predictors of window opening during the intermittent period for each season are shown in Table 5-22.

Table 5-22: Significant predictors of window opening during the intermittent period for summer, autumn and winter

Arrival predictors	Summer	Autumn	Winter
Indoor temperature	✓	✓	✓
CO_2 concentration		✓	✓

In the summer, indoor temperature was the significant predictor of window opening during this period. Indoor temperature accounted for 3.4% of the variation in the observation. The largest percentage of windows remaining in the same state was recorded in this season, with approximately 63% of windows remaining in the open state. The maximum CO_2 concentration recorded in the summer during the intermittent period was 2860ppm. However, CO_2 measurements over 1000ppm made up only 13.5% of the summer CO_2 data set and concentrations less than 500ppm made up approximately 52% of the measurements. Since most windows remained in the open state when they had been opened on arrival, the low levels of CO_2 concentration were maintained. Having only a small percentage of CO_2 concentration above 1000ppm, conditions were not present in order to detect an impact of CO_2 concentration on window opening.

In the autumn, indoor temperature and CO_2 concentration were the significant predictors of window opening and in winter, CO_2 concentration was the only significant predictor. The mean CO_2 concentrations recorded in the summer was 677ppm and in the autumn and winter, they were 857ppm and 844ppm respectively. The difference between the autumn and winter measurements is only marginal and there is also a higher frequency of CO_2 concentrations greater than 1000ppm in these seasons compared to the summer measurements. It was therefore possible to determine the influence of CO_2 concentration on window opening in these seasons and the results indicate that with increasing CO_2 levels, there is increasing likelihood of window opening. The influence of indoor temperature also confirms that there will be a difference in response to CO_2 concentration in different internal thermal conditions as shown in Figure 5-16. In the winter season, although the indoor temperature and CO_2 concentration are significant predictors of window opening, they both account for a modest amount of the variation in the observation (2% and 3% for indoor temperature and CO_2 concentration respectively). This may suggest that other variables which have not being monitored in the current indoor survey may have a bigger influence on window opening during the intermittent period in the season. Table 5-23 presents the regression parameters for window opening during the intermittent period for each season. All predictors were significant at $p < 0.05$.

Table 5-23: Regression parameters for window opening during intermittent period in the summer, autumn and winter seasons

Season	**Environmental variable**	a	b	**Nagelkerke's** R^2
Summer	Indoor temperature	-16.92 ± 1.17	0.75 ± 0.05	0.359
Autumn	Indoor temperature	-10.73 ± 0.88	0.47 ± 0.04	0.160
	CO_2 concentration	-7.69 ± 0.89	1.18 ± 0.13	0.050
Winter	Indoor temperature	-0.88 ± 0.54	0.03 ± 0.02	0.020
	CO_2 concentration	-13.95 ± 1.24	2.13 ± 0.19	0.030

The above season-specific analysis has shown the role of indoor temperature and CO_2 concentration on window opening during the intermittent period. The results show that thermal conditions always play an important role in window opening. However, in different thermal environments, parameters other than temperature begin to have an impact on occupant behaviour.

5.9 Summary

A selected number of individual offices were monitored in the summer, autumn and winter seasons in a continuous indoor survey. Although this provides a much smaller number of windows to be investigated than the outdoor survey it allows a more in-depth analysis of the influencing variables, particularly the measurement of the indoor environment. In an advance on previous surveys this study has measured internal CO_2 concentration as well as temperature and relative humidity.

Encouragingly the initial investigation using univariate analysis showed similar results to previous surveys. Indoor and outdoor temperatures were the best predictor of windows being in the open state. Assessment of the window position allowed the results to be compared to the photographic survey and previous studies. This will be presented in Chapter 7. Following this the data was adapted to consider the role of the previous 5 minutes when a window changed state. This is important in investigating the factors that influence occupants' window opening behaviour, rather than simply correlating the environmental conditions to a window position. Window opening was therefore investigated at different time periods in the day. In the time dependent analysis, there was a variation in the variables that influence window opening on arrival, during occupancy and at departure. An important observation in the intermittent period was the significant influence of CO_2 concentration and indoor temperature. The result showed that the probability of window state changing from closed to open increases with increasing indoor temperature and increasing CO_2 concentration, indicating that at higher CO_2 levels occupants will adjust their environment accordingly.

Due to the interesting observation of the nature of outdoor temperature in predicting window opening, a season-specific analysis was conducted for the arrival and intermittent periods. The results showed that occupants' window opening as a function of thermal conditions varies due to seasonal changes. In the colder seasons, on arrival, the probability of window opening was found to increase with decreasing outdoor temperature and during the intermittent period, CO_2 concentration was a significant predictor of window opening only in the autumn and winter season. The negative correlation with outdoor temperature on arrival suggests that other factors such as direct solar gain and the resulting mean radiant temperature, thermal shock and transition between different thermal environments may also influence window opening.

The arrival period did not show any effect of CO_2 on the occupants' behaviour. However, this may be because the conditions were not present to study this. In order to investigate this role of CO_2 further Chapter 6 explains a controlled experiment conducted to test whether occupants will open windows during short periods in conditions of high CO_2 concentrations.

6 Window opening on arrival

6.1 Introduction

6.2 Experimental conditions

6.3 Questionnaires and tests

6.4 Experimental procedure

6.5 Initial observations

6.6 Association between initial environmental conditions and window opening

6.7 Evaluation of perceived environment

6.8 Association between perceived environment and window opening

6.9 Sensitivity analysis

6.10 Summary

6.1 Introduction

In Chapter 5, in order to investigate the conditions that influence a change in window state, the parameters occurring just before window opening were investigated in a time dependent analysis. In the arrival period only temperature mattered. However, during the intermittent period the probability of window opening increased with increasing indoor temperature and CO_2 concentration. This is an important finding as it shows that the probability of windows opening increases with increasing CO_2 concentration. There is however a difference in probabilities of window opening at different indoor temperatures: at a given CO_2 concentration, the probability is lower at a lower indoor temperature compared to a higher temperature. This indicates that in different temperature conditions, occupant behaviour will be different. Indoor temperature may act as a suppressor parameter and hence it is important to investigate the influence of CO_2 concentration in different thermal conditions (thermally comfortable and uncomfortable conditions).

That CO_2 concentration did not influence window opening in the arrival period could be because the conditions necessary to observe occupants' response to high CO_2 concentration were not present. As a first step, the influence of CO_2 concentration on window opening in the arrival period was investigated. An experiment was designed in order to observe occupant behaviour in pre-set environmental conditions. The following sections present the details of the experimental setup and procedure which ensured that the experiment was successful.

6.1.1 Aim

The experiment on window opening behaviour occurring within a short period after arrival described was conducted to investigate the influence of CO_2 concentration. In addition, it demonstrates a low cost, robust and safe methodology for investigating the influence of drivers for window opening.

In this experiment, individual participants were exposed to one of four environmental conditions, combinations of two air temperatures and two CO_2 concentrations. In an experimental session, the indoor climatic conditions were recorded whilst participants completed a set of questionnaires to record their perceived environment and control. They had some control of the environment and this included the use of all available adaptive measures. The experiment was approved by the ethics review board in the Department of Civil and Structural Engineering, University of Sheffield.

6.2 Experimental conditions

The experiment was conducted using four environmental conditions – two levels each of indoor temperature and CO_2 concentration. The temperatures were low at 20°C (here after referred to as comfortable) and high temperature at 28°C and the CO_2 levels were low (hereafter referred to as ambient) and high at 3000ppm. The combinations of these conditions were: comfortable temperature and ambient CO_2, comfortable temperature and high CO_2, high temperature and ambient CO_2, high temperature and high CO_2. No other indoor variables were controlled.

6.2.1 Indoor temperature

The low and high temperatures were selected to have thermally comfortable and uncomfortable conditions that had a clear difference in the probability of window opening. From Figure 5-10 in Section 5.5.1, at 20°C and 28°C, the probabilities of window opening were 0.34 and 0.69 respectively. The probability at the high temperature is double that at the low temperature and so a clear difference in window opening can be expected. In addition to the difference in probabilities of window opening, earlier studies have shown that an indoor temperature of 20°C, corresponds with an 80% acceptability of the thermal environment (Brager & de Dear 2001). Hence 20°C is considered as an acceptable temperature in which majority of participants will be thermally comfortable. Also since the probability of window opening is high at 28°C, this thermal condition is used to check that participants will open a window despite being in a room they have no ownership of.

6.2.2 CO_2 concentration

Ambient conditions were used for the low CO_2 concentration, which in a typical single person office similar to the one used in the experiment and the average ambient CO_2 concentration recorded was 464ppm. A CO_2 concentration of 3000ppm was selected for the high CO_2 environments. This concentration is significantly higher than ambient concentration so any overlaps in initial CO_2 conditions will be avoided and it will allow for any possible influence of high CO_2 on window opening to be observed. A concentration of 3000ppm is higher than the level at which physiological effects on occupants occur (Carpenter & Poitrast 1990; Tsai *et al.* 2012). However, it is also lower than the recommended level set by the Workplace Health and Safety Executive (HSE 2011) and therefore poses no safety concerns for the participants. At a concentration of 3000ppm, the impact and response from expected from occupants include complaints of drowsiness, sleepiness, reduced attention, headaches and poor air quality (stale or stuffy).

6.2.3 External conditions/weather

Weather data was collected from the weather station described in Chapter 3. The parameter of interest in the controlled experiment was CO_2 concentration in comfortable and high indoor temperatures and so weather information was required to assess the effectiveness of the methodology by evaluating whether outdoor environmental conditions had an impact on occupant's responses.

6.2.4 Establishing initial conditions

A portable electric heater with a thermostat was used to increase the indoor temperature. To increase the CO_2 concentration, dry ice was selected as the safe and low cost CO_2 injection technique. CO_2 injection methods will be explained further in Section 6.2.4.1. A portable electric fan was used to ensure circulation of air when the dry ice was exposed to reduce accumulation of CO_2 concentration in different locations in the room. A set-up test was conducted using multiple data loggers to measure CO_2 concentration at different locations in the room when dry ice was exposed to observe where there could be possible accumulation of CO_2 gas. Details of the set-up test are presented in Section 6.2.4.2. The electric heater, dry ice and fan were removed before participants entered the office.

6.2.4.1 CO_2 injection techniques

Dry ice is the solid state of CO_2 and it is often used as a coolant in the food and pharmaceutical industry. Using dry ice to increase the CO_2 level is a simple method which poses little health and safety risks and was easy to handle and transport. It changes state from the solid form directly to gas form as there is no liquid state. It can be supplied in pellet form which sublimate at a faster rate compared to the block form. The pellet form can be supplied in 5 or 10kg bags, making it easier to handle manually. In these experiments, the room needed to be cleared of all set-up equipment before occupants entered and so using dry ice in a small box was easy and safe. Dry ice is also cheaper to purchase compared to the alternative injection methods (e.g. CO_2 gas cylinder).

6.2.4.2 Set-up test

A set-up test was conducted to assess the effectiveness of using dry ice to increase the CO_2 concentration by ensuring uniform mixing of the gas and examining the effect of door opening on the initial conditions (as the door will need to be opened to let the occupant enter). A calculation was carried out to establish an approximate amount of dry ice needed to increase the indoor CO_2 level from ambient level to 3000ppm. Based on the volume of the test office, the amount of dry ice required was calculated to be approximately 0.2kg.

Dry ice left in the open at room temperature will sublimate at a rate of 14% of total mass per hour (Imperial College London 2004). Assuming a 30 minute set-up time, approximately 3kg of dry ice would be needed to increase the CO_2 level to 3000ppm for one experimental session. Because oxygen represents approximately one-fifth of the total volume of atmospheric air, for 5% of a displacing gas introduced into a confined space oxygen concentration is depleted by 1%. Therefore a 0.063% of oxygen gas is indicative of a 0.315% or 3150ppm addition of another gas, which is CO_2 in this case. As a safety check, the percentage of oxygen in the room after CO_2 injection was calculated. Concentrations of room oxygen greater than 18% are considered safe for breathing (University of Sheffield 2011). With an increase of CO_2 concentration to 3000ppm, the room oxygen concentration will be depleted by 0.063%. The percentage of oxygen available for breathing therefore does not exceed the 18% safe limit making the room safe for both the experiment administrator and the participants.

The set-up test using eight data loggers placed in different locations in the office to record CO_2 concentration when the dry ice was sublimated. Figure 6-1 shows photographs of some of the logger locations in the test office and a photograph of when the dry ice and fan were placed in the office

The loggers were placed on three different levels – top level (on a book shelf) at a height of 1.7m from the floor (head height); middle level (on a table, by the window, on the drawers and by the door) at a height of 0.725m from the floor; and floor level. The middle level represents the approximate area where conditions will affect a seated occupant. The loggers were placed at different locations across the room (on a horizontal plane) – at the window, in the middle of the room at a distance of 2.4m from the window and by the door, 4.7m opposite the window. The dry ice was placed on the table and the fan was turned on with the oscillating function activated to enable mixing of air. The loggers recorded CO_2 concentrations at one second intervals. The insulated box containing the dry ice was placed in the room at the start of the test and the fan was switched on.

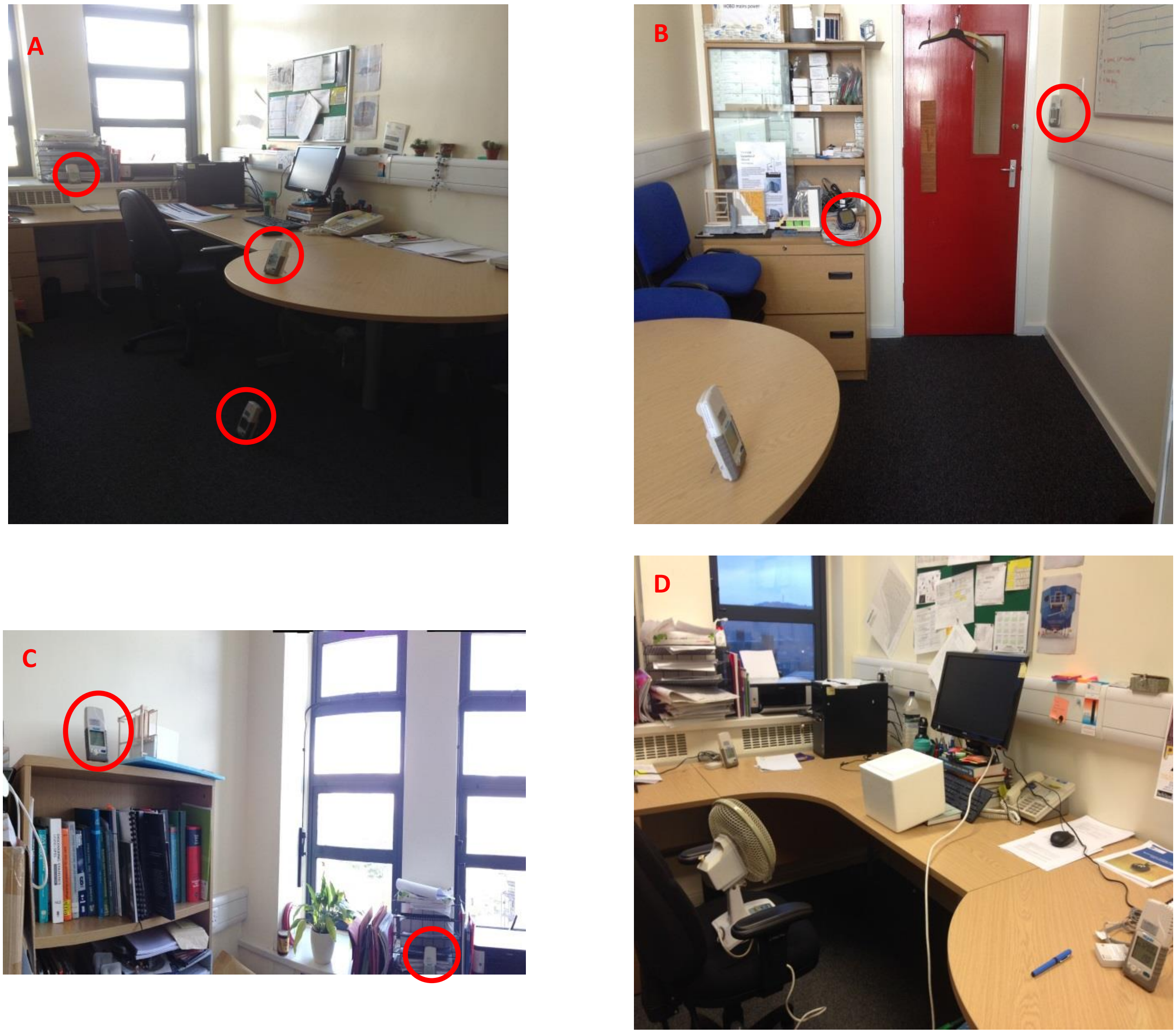


Figure 6-1: Photographs of test office showing some logger locations (A-C) and dry ice with fan (D)

The results of this set-up test are presented in Figures 6-2 and 6-3. Figure 6-2 shows the variation in CO_2 concentration in the vertical plane and Figure 6-3 shows the variation in CO_2 concentration measured in a horizontal plane (across the middle level in the office). On the vertical plane, at the top level, CO_2 was 3002ppm at 27 minutes, at the middle level, it was 3029ppm at 23 minutes and on the floor, it was 3018ppm at 24 minutes. Since CO_2 gas is denser than air, it makes sense for the floor level to reach the required concentration before the middle and top level. For the horizontal plane, at the window, CO_2 was 3005ppm at 22 minutes, on the table and at the door it was 3041ppm 3013ppm respectively at 24 minutes. The measured concentrations show that using the fan is effective in achieving an acceptable mixing of CO_2 in the room and the required concentration can be achieved in approximately 24 minutes after the dry ice is allowed to sublimate in the test office. After 24 minutes, the difference between the top and floor concentration is 172ppm and the difference between the middle and the floor concentration is 11ppm. These differences are acceptable as all the concentrations are sufficiently greater than the ambient level and hence there will not be any overlapping of the ambient and high CO_2 levels.

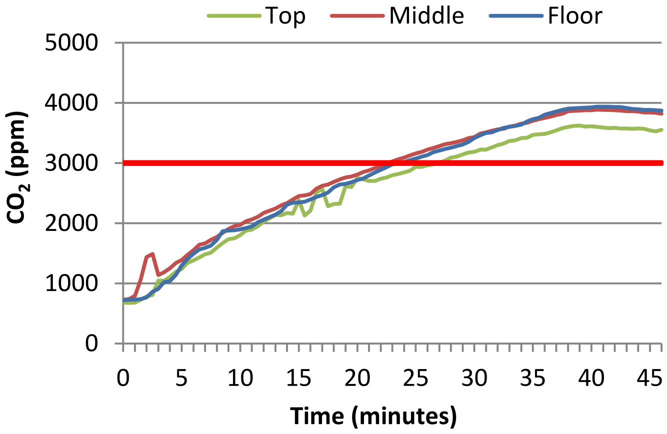


Figure 6-2: CO_2 measurements at the different locations in the office: variation along the vertical plane

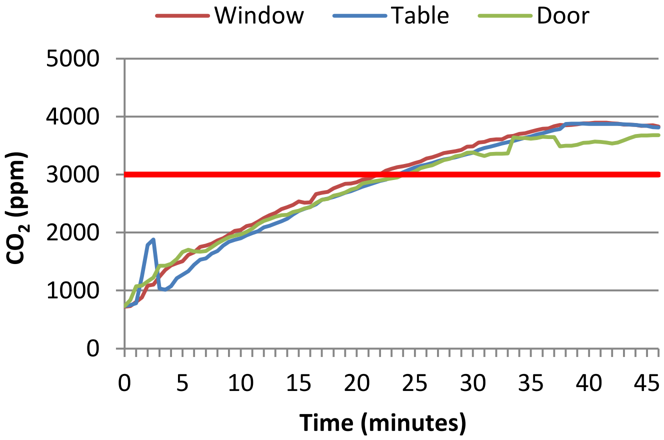


Figure 6-3: measurements at the different locations in the office: variation along the horizontal plane

The effect of door opening on the CO_2 concentration was also analysed. This was necessary to ensure that the desired initial high CO_2 concentration was maintained when the door was opened for entry at the start of the experiment. Observations from the indoor survey showed that the total time for door opening and closing for entry or exit only were between three and six seconds. A door opening duration of five seconds was selected for the set-up test. The windows remained closed for this test.

After the CO_2 concentration had been increased to approximately 3500ppm, the door was opened and closed and the CO_2 concentration at the table was measured for a further 30 minutes. The decrease in CO_2 concentration after the door had been opened and closed is shown in Figure 6-4. At this logger location, CO_2 concentration reduced by approximately 363ppm. This demonstrates that short term door opening will have little effect on the initial high CO_2 condition required for the experiment. Again, there will not be an overlap in CO_2 conditions when the door is opened for entry. Figure 6-4 also shows that CO_2 concentration will remain higher than the ambient concentration for the duration of the experimental session if a window is not opened.

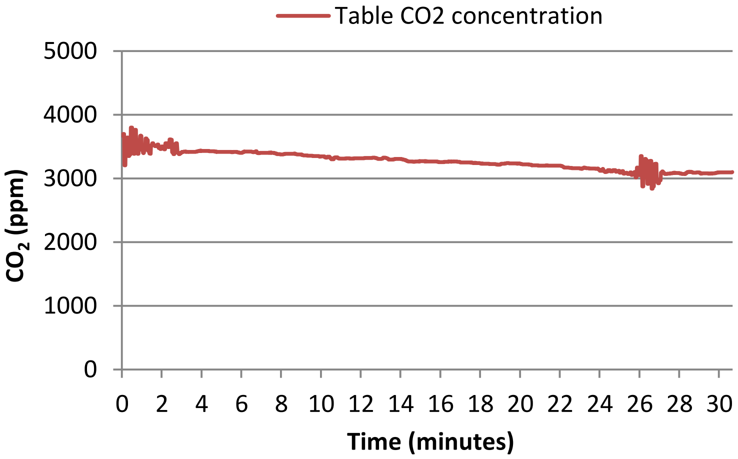


Figure 6-4: Decrease in CO_2 concentration after door opening: CO_2 measured at the table for 30 minutes after door opening

6.2.5 Offices

Tests were carried out in five different offices. It would be preferable to use just one room but this was not possible. All of these offices were single person rooms, naturally ventilated with four accessible and operable windows. There were two windows on lower level and two on a higher level (Figure 6-5A) and they could open up to 0.2m wide. Windows on the higher level were accessible and opened by chain openers with handles located on lower levels. Details of the offices are presented in Table 6-1 and Figure 6-5 shows pictures of the window and the data loggers. All offices were for University of Sheffield academic staff and were equipped with the usual office furnishings (carpet, desk and office chair, book cases/shelves) including electrical gadgets (desktop computer, printer and telephone). All the offices were painted a neutral colour.

Table 6-1: Details of offices used for the experiment

	Office 1	**Office 2**	**Office 3**	**Office 4**	**Office 5**
Floor level	Second	Third	Third	Third	Third
Orientation	North	South	North	North	North
Time used	Nov – Dec 2011	Feb – Mar 2012	June & Sept 2012	Aug 2012	Oct 2012
Number of experiments	24	20	30	35	40

Figure 6-5: Photographs of the windows and the data loggers in a typical office used for the experiment: A – Test office with environmental data logger B – Lower and upper windows and chain opener for upper window; C – State logger on lower window

6.2.6 Sample size

For this current experiment, there were two levels of the predictor variable and two levels of the outcome variables and each participant would provide one set of data. The difference in the outcome variable (window opened or not opened) between the two levels of initial environments (e.g. ambient and high CO_2) would be tested. To determine the sample size required for the experiment, the standard threshold *p*-value of 0.05 was used and the common statistical power of 80% was also applied. From Section 5.5.1, at high temperature of 28°C, the probability of window opening is 0.69 hence a large effect size and statistical power of 0.8 were specified. The effect size is the strength of phenomenon, e.g. the strength of indoor temperature on window opening and power is the probability that the observation correctly rejects the null hypothesis. Cohen (1992) published tables of sample sizes based on the statistical test, the effect size and the statistical power. From his tables, a minimum sample size of 26 participants would be required for participating in each initial environment. A power analysis is useful to justify the power of an experimental study and to ensure that every aspect of the study has been thought through thoroughly. However, one limitation is that it can sometimes underestimate the sample size as the result is often the minimum limits or the best case scenario based on assumptions which can result in inadequacies in the statistical analysis of the data collected (IDRA 2014). In this study, the sample size of 128 participants (32 participants in each environment) was considered to be adequate to allow for a practical difference to be observed and analysed. Studies investigating the influence of CO_2 concentration on performance have used sample sizes between 10 -30 participants (Kajtar *et al.* 2003; Satish *et al.* 2012).

6.2.6.1 Recruiting participants

Participants were recruited to individually take part in the experiment. An invitation to participate in the experiment was sent out via email to all staff and students at the university. Posters and leaflets were also used to advertise for participation at the required times. The email and poster requested for participation in a study of the influence of indoor environmental quality on work performance which would require completing a set of questionnaires in a fully furnished single person office. Details of the environmental conditions were not revealed in order to avoid bias in the results and also to allow participants to work like they normally would in real life. A chance to win a gift voucher worth £50 was also included in an attempt to increase the potential participant response rate.

In total 149 participants took part in the experiment. Each participant contributed one set of results to the study. Of these, 21 were discounted after completing the test because of unacceptable initial conditions and failure of equipment. In cases where the desired high temperature and/or CO_2 concentration was not achieved and where the data loggers failed to record the environmental conditions, the results were excluded from the data set. The final number of participants whose results were analysed was 128, with 32 in each environment. This sample size is slightly greater than that specified by Cohen but the statistical properties (effect size, α and power) are the same.

6.2.7 Trial duration

In Chapter 5, during the arrival period (i.e. up to 5 minutes following arrival) the maximum recorded CO_2 concentration was 1342ppm. This concentration level in the arrival period was not high enough to investigate its influence on window opening compared to the intermittent period (maximum = 3353ppm) where CO_2 was linked to window opening. Hence the short-term reaction, to represent arrival period, to CO_2 concentration is investigated in this experiment. Since most window opening occurs on arrival (as shown in Table 5-8), minimum experiment duration of 30 minutes was selected to represent the arrival period.

On adaptation using available controls, Hellwig *et al*. (2008) noted that due to adaptation, occupants are not able to assess the quality of indoor air when they stay longer than 15 minutes in the same room. As occupants respond more readily to their thermal environment and adapt their environment and/or themselves primarily based on thermal sensation, this is more likely to happen closer to their entry into the room. If occupants are thermally comfortable or if they employ an adaptive measure such as adjusting their clothing, they may grow accustomed to their environment within 15 minutes and not assess the quality of the indoor air. Considering sensitivity to odours, for periods over 30 minutes, occupants become less sensitive to any odours present (CIBSE 2006).

6.3 Questionnaires

For the experiment, two questionnaires were administered to the participants to record their perceptions of the environment and control and paper-based tests were administered to simulate office activity. These were designed with the help of standard environmental questionnaires and psychometric type tests.

6.3.1 Perceived environment questionnaire

The environmental and comfort evaluation questions were on several aspects of the environment: sound (external noise), lighting (natural light and artificial light), air quality, ventilation, thermal comfort, odour, humidity, furnishing (seating comfort) and general ambience in the office. Responses were gained using an environmental voting scale. Since only two levels of thermal conditions and two levels of CO_2 conditions were being considered in this experiment, the traditional seven-point thermal comfort scale such as the ASHRAE thermal sensation scale (ASHRAE 2010a) was adjusted to produce a simple two and three-point scale for evaluating thermal comfort and the other aspects of the environment. Table 6-2 presents the descriptions provided to evaluate the environment.

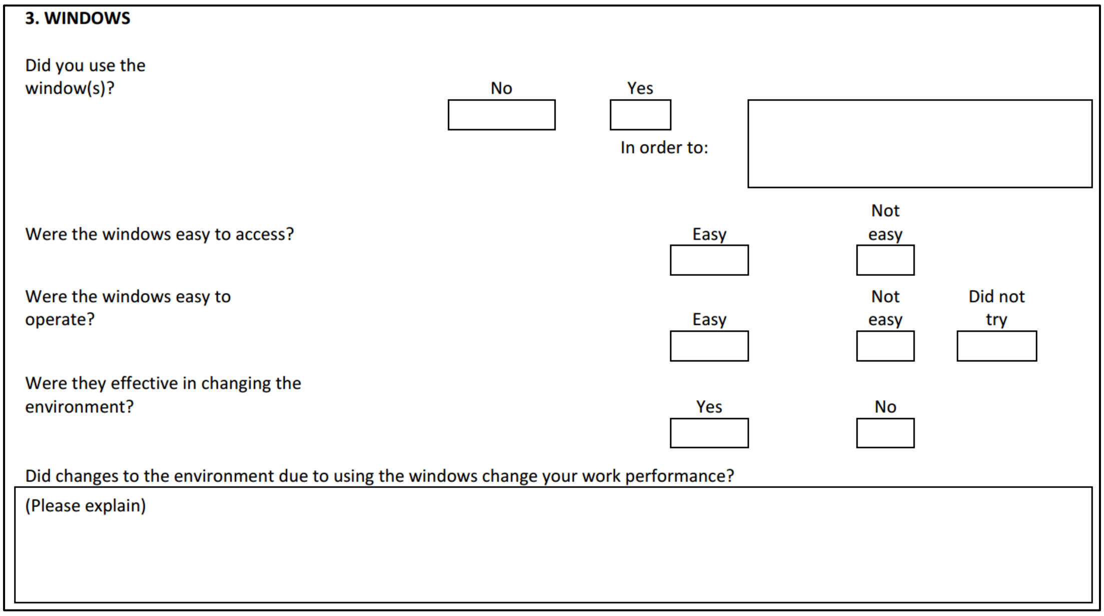
Table 6-2: Descriptions used to evaluate the perceived environment and comfort

Condition	**Description**
Thermal comfort	Too warm
	Comfortable
	Too cold
Air quality	Fresh
	Stale
Odour	Acceptable
	Unacceptable
Ventilation	Good
	Poor/Stuffy
Humidity	Too humid
	Just right
	Too dry
Sound (external noise)	Distracting
	Acceptable
Lighting (natural and artificial)	Too much
	Just right
	Not enough
Seating position	Comfortable
	Not comfortable
General ambience	Good
	Acceptable
	Bad

The questions were designed to be simple, short and to avoid loaded and leading which suggests particular answers. For instance the question for thermal comfort was: How does the room temperature feel? All the questions were closed with tick boxes provided. This was necessary as the experimental sessions were individual sessions with no intervention or interruptions from the researcher. A ‘comment’ box was included at the end to allow participants to add additional information if so desired. This environmental and comfort evaluation questionnaire was completed twice, one at the start of the session (Questionnaire 1) and the other after the paper-based tests had been completed (Questionnaire 2), in order to evaluate any changes in perceived environment.

6.3.2 Perceived control questionnaire

A second questionnaire (Questionnaire 3) was used to record adaptive processes employed and reasons for these processes. Questions were asked on adjusting light levels (using mains light, desk lamp or adjusting blinds/curtains), opening a window, adjusting seating, adjusting clothing and response to external noise. Participants were asked if any of the controls were used, if they were easily accessible and if they were effective in improving the environmental conditions. Similar to the perceived environment questionnaire, questions were closed and tick boxes for ‘Yes’ and ‘No’ were provided to record responses on whether a not a particular control was used. A follow up question was linked to the ‘Yes’ tick box to record why the control measure was used. Again, a ‘comment’ box was included at the end to allow participants to add more information if they wanted to. Figure 6-6 shows a section of the question on the use of window as an example of the questions on perceived control. This questionnaire was completed at the end of the experimental session before the participant vacated the office.



3. WINDOWS

Did you use the window(s)?	No ☐	Yes ☐ In order to:	☐
Were the windows easy to access?	Easy ☐	Not easy ☐	
Were the windows easy to operate?	Easy ☐	Not easy ☐	Did not try ☐
Were they effective in changing the environment?	Yes ☐	No ☐	

Did changes to the environment due to using the windows change your work performance?

(Please explain)

Figure 6-6: Section of the questionnaire on perceived control relating to window use

6.3.3 Reliability and validity of responses

In a questionnaire survey, it is important that both the author and the respondents interpret the questions and the answers in a similar manner. This is even more important when the author is not present during the time the respondent is completing the questionnaire. When questionnaires are administered with an interviewer present, questions and answers can be clarified at the same time. A pre-test is often useful to ensure that both the author/researcher and the respondent have similar understanding of the questions and answers. A pre-test will offer feedback on the clarity of information provided and it will give an indication of whether the answers provided reflect the aims of the study. The pre-test is also useful in determining the estimate of the length of time it will take to complete the questionnaire. Other concerns that can be highlighted in a pre-test are unnecessary repetition in questions, appropriate choice of answers provided and missing or overlooked information that could be useful in the study (Oppenheim 2005).

A pre-test was conducted where five colleagues were asked to complete the questionnaires and provide feedback on the questions and the answers and the time it took. At the start of the pre-test instructions were given to the participants similar to what would have been to the participants in the experiment. The feedback given after this pre-test was the need for more clarification on why Questionnaires 1 and 2 were identical. It was suggested that this had to be clearly explained in order to avoid the risk of participants not completing it. The other feedback given was on the time it took to complete each questionnaire. The average amount taken to complete Questionnaires 1 and 2 was approximately four minutes (two minutes on each) minutes and for Questionnaire 3 it was five minutes. The total time for one experimental session was therefore estimated as 39 minutes.

Participants were blinded to the initial conditions of the experiments implying that responses given in the questionnaires were more likely to be based on their perceived environment and comfort rather than their knowledge of the actual environmental conditions. This is a good check for the validity of the responses provided. The main objective of experiment was to observe window opening behaviour. State loggers were mounted on the windows to record window use and the data was used to cross check against the response provided for the use of windows as an adaptive measure. This was also a good check for the validity of the responses.

6.3.4 Paper-based tests

Numerical computation and data-checking tests, similar to psychometric or aptitude tests often used as part of job hiring process, were used in the experiment. Each test comprised of 40 multiple choice questions. The use of a calculator was not allowed in the numerical test. The time allocated to each test was 15 minutes and participants were asked to answer as many questions as they could in that time. The advertisement requesting for participation in the experiment suggested that an investigation of the influence or environmental conditions on performance was being conducted. The advertisement was designed as such so as to keep the participants blinded to the initial environments conditions, particularly the CO_2 conditions and also to the actual objective of the experiment which was window opening behaviour. Occupants were also required to spend at least 30 minutes in the test office for the experiment. Hence the role of the paper-based tests was to keep the participants occupied for the observation period. Numerical computation and data-checking tests were selected to simulate office type tasks which would be in line with the study that was requesting for participation as advertised in the email, leaflets and posters. The tests were only used as a distraction for the participants and so the results were not analysed.

6.4 Experimental procedure

Participation in the experiment was in individual sessions. This was to allow participants maximum control of the environment by avoiding doubt over ownership and also to create conditions close to those in the indoor survey where individuals in single person offices were observed. Figure 6-7 shows the timeline of a typical environmental session. The participant was brought into the test office by the experiment administrator who explained the purpose of the study as advertised. Additional information and instructions were given on available adaptive measures and completing the questionnaires and test.

Participants were informed that they were free to use all available environmental control measures (light switch and desk lamp, windows, blinds/curtains, seating and their clothing). All windows were closed before the participant was brought into the test office. They were then given instructions on completing the questionnaires and tests. These had to be completed in the order in which it had been presented to them – Questionnaire 1, Test 1 and 2, Questionnaire 2 and then Questionnaire 3. It was explicitly pointed out that Questionnaires 1 and 2 were identical but they were recording perceived environment at different times. For the tests, participants were asked to answer as many questions as they could, spending 15 minutes on each test. All the instructions were also provided in the front cover of the paper work. Participants were informed that they were free to terminate their participation and leave the office at any time during the session. None of the participants exercised this option.

During the session, state monitors mounted on the windows recorded the time that a window was opened and indoor environmental conditions (air temperature, relative humidity and CO_2 concentration) were recorded at one minute intervals using one environmental data logger. Details of data loggers are presented in Chapter 3. The logger was placed on the table to record the environmental variables closely affecting the participant without it causing a distraction. Having the logger in the working area of the occupant is similar to previous studies which have conducted subjective surveys using questionnaires and interviews to investigate window opening behaviour where they have recorded indoor environmental conditions, usually temperature, at the desk of the occupant (Rijal *et al.* 2007).

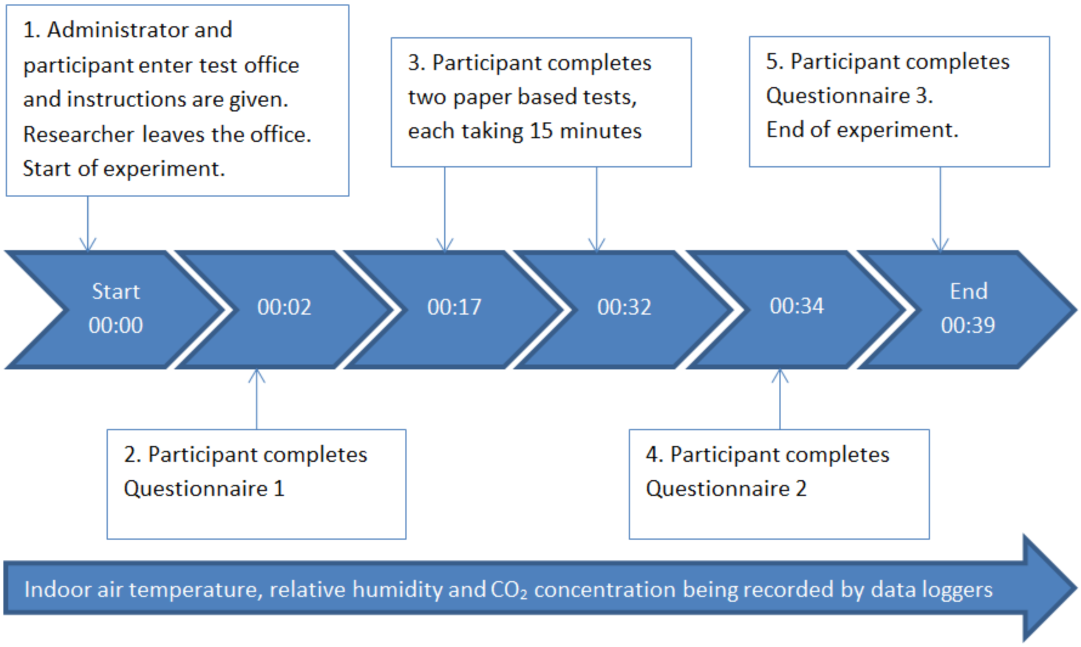


Figure 6-7: Timeline of a typical experimental session for the experiment with controlled conditions

6.5 Initial observations

Participants recruited were primarily staff and students of the University of Sheffield. All participants were at least 18 years old. In total, 149 people participated in the experiment, resulting in an average of 96.9 hours of experimental time. In the experiments that were taken forward for analysis, the participants comprised of 81 males (63%) and 47 females (37%). There was a variety of nationalities represented in the sample and so geographic origin was divided into five groups: UK, Europe, Asia, Africa and the Americas. Participants from the UK and Asia made up the biggest proportions (45% and 33% respectively). Participants from other European countries accounted for 11%, from African countries it was 9% and 2% from the Americas.

Even though the initial experimental conditions were controlled, there were challenges in achieving the exact temperatures and CO_2 concentrations proposed. Infiltration of outdoor air due to uncontrolled ventilation and solar radiation penetrating into the office were not prevented. The initial temperature would be affected by both the uncontrolled ventilation and solar radiation and CO_2 concentrations would be affected by the uncontrolled ventilation resulting in variability in the initial values. Other indoor air pollutants were not measured and indoor relative humidity was measured but not controlled. Table 6-3 shows the details of the initial temperature and CO_2 parameters achieved and Figures 6-8 and 6-9 present the frequency of the achieved initial temperature and CO_2 concentrations respectively. Even though there was variation in the initial conditions, very importantly, there were no overlaps between the comfortable/ambient conditions and the high conditions.

Table 6-3: Initial indoor temperature and CO_2 concentrations achieved

Initial condition	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Comfortable temperature (°C)	17.3	22.5	20.4	1.12
High temperature (°C)	26.9	32.2	29.1	1.23
Ambient CO_2 (ppm)	379	882	550	122
High CO_2 (ppm)	2718	3686	3265	288

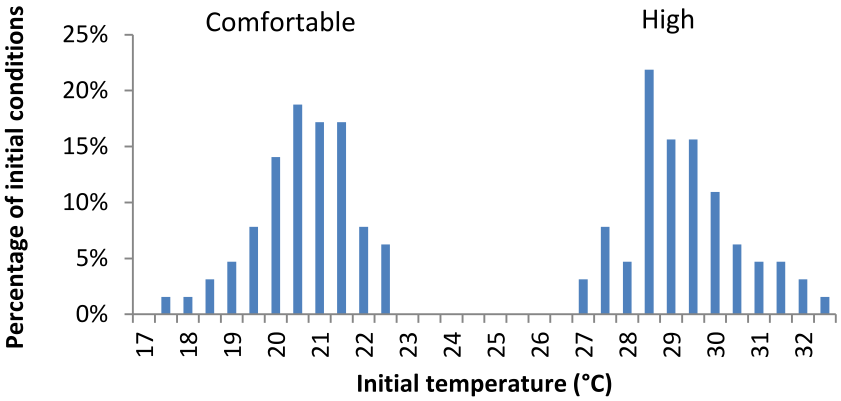


Figure 6-8: Initial temperatures recorded in the comfortable and high temperature settings

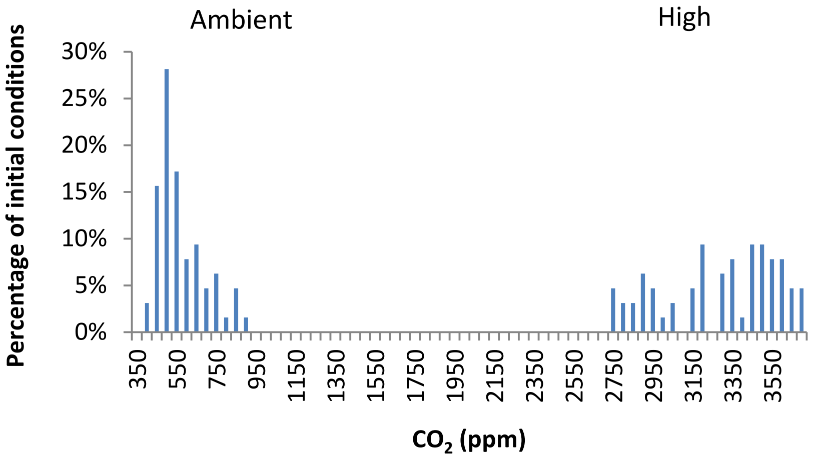


Figure 6-9: Initial CO_2 recorded in the comfortable and high CO_2 settings

The recorded relative humidity during the experiment is presented in Table 6-4. Initial relative humidity was not controlled for the experiment. The average humidity recorded in the experiment with high temperature conditions was almost 10% lower than that recorded in the comfortable temperature experiments. Humidity will later be examined for any possible association with perceived environment.

Table 6-4: Indoor relative humidity measured in each temperature environment during the experiment

	Comfortable temperature	**High temperature**
Minimum	29.5%	18.5%
Maximum	64.1%	52.2%
Average	45.2%	35.6%
Standard deviation	9.9%	8.0%

Experimental sessions were carried out from July 2011 to October 2012. A range of outdoor temperatures were therefore observed during the experiment. Outdoor temperature was obtained from the weather station described in Chapter 3. The maximum daytime temperature recorded was 23.0°C, minimum daytime was 2.3°C and the average was 13.6°C. Table 6-5 presents the outdoor temperatures recorded for each of the defined environments. The experiments were carried out in a random order. With the exception of the comfortable temperature environment with the high CO_2 condition, the other three environments had very similar average outdoor temperatures. Since in Chapter 5 an association was found between outdoor temperature and window opening, outdoor temperature will later be examined for any possible association with window opening.

Table 6-5: Outdoor temperature during the experiment

	Outdoor temperature (°C)			
Initial environment	**Minimum**	**Maximum**	**Average**	**Standard deviation**
Comfortable temperature Ambient CO_2	9.3	19.5	14.6	2.6
High temperature Ambient CO_2	5.9	22.7	14.8	4.8
Comfortable temperature High CO_2	2.3	18.7	11.0	5.9
High temperature High CO_2	8.5	23.0	14.9	3.9

During the experiment, window opened on arrival was determined from the time the participant started the experiment (after the researcher had left the office) and the time indicated by the window state logger for a change in state. If window opening occurred within 5 minutes of start of the experiment, it is categorised as on arrival. Any window opening after this time was categorised as intermittent. These time periods have been defined based on the observations from the indoor survey presented in Chapter 5. The observation of time of window opening is in line with the observations in Chapter 5. From the current experiment, Figure 6-10 shows a clear distinction in window opening on arrival and during the intermittent period in all the environments defined. There was very little difference in proportion of windows opened either on entry or during intermittent occupancy between the environments. In all four environments an average of 84% of window opening was carried out on arrival. The observation presented in Figure 6-10 shows that occupants who opened windows tended to do so on arrival than later (within the 30 minute period).

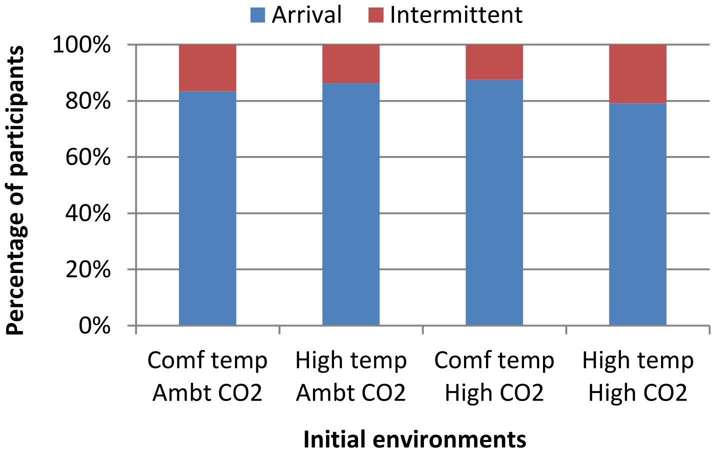


Figure 6-10: Proportion of participants who opened windows on arrival and during the intermittent periods

6.6 Association between initial environmental conditions and window opening

Window opening in the initial environments is presented in Figure 6-11. The aim of the experiment was to observe window opening behaviour and environments were created to force window opening. The results presented in Figure 6-11 also show that participants did open the window. Even though the participants did not own the space, they did take action to adapt the room. This indicates that the experiment methodology was effective in prompting window opening when the participant needed to adjust their environment.

The overall window opening pattern showed that more participants in the high temperature environments opened windows compared to those in the comfortable temperature environments. This was irrespective of the initial CO_2 concentration. In the high temperature environments, 69% and 75% of occupants opened the window in the ambient CO_2 and high CO_2 conditions respectively. In the comfortable temperature environments the values were 19% and 25% in the ambient and high CO_2 conditions respectively.

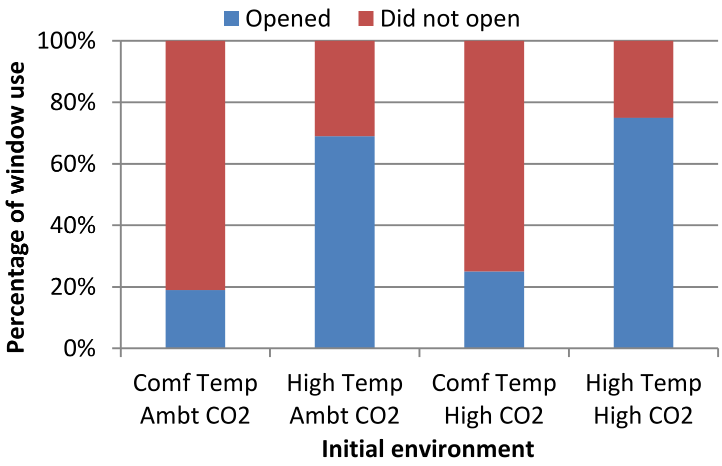


Figure 6-11: Variation of window opening in each initial temperature and CO_2 condition

Statistical analysis was conducted to determine the relationship between the initial conditions and window opening. Temperature and CO_2 were analysed separately to determine the strength of their association with window opening.

Binary logistic regression was used to assess the difference in window opening between the initial environments defined. For this analysis, both temperature and CO_2 conditions were added to the model. The χ^2 value for the overall model was 34.33 at a significance of less than 0.001 and the Nagelkerke R^2 was 0.314, implying that a combination of temperature and CO_2 could explain 31.4% of the variance in window opening observed. A chi-square analysis was conducted to assess the individual contribution of temperature and CO_2. In the chi-squared analysis, all the expected frequencies were greater than 5, making this test appropriate for the data. The analysis showed that there was an association between the thermal environment and window opening. Initial temperature was found to have a strong influence on occupant window opening behaviour. The calculated χ^2 for initial temperature was 32.1 at a significance level of 0.01 (the critical χ^2 for a 0.01 level of significance is 6.64). Using comfortable temperature as the reference variable, participants in the high temperature environment were nine times more likely to open a window than those in the comfortable temperature environment. There was no significant association between CO_2 concentration and window opening. Using the ambient CO_2 environment as the reference variable, participants in high CO_2 conditions were only 1.3 times more likely to open a window compared to participants in ambient CO_2 conditions, however this was not significant. The χ^2 calculated was 0.502 and the significance level was 0.476. Temperature explained 30.9% of the variance and CO_2 explained an additional 0.5%. The interaction of temperature and CO_2 concentration was also examined using logistic regression. There was no relationship between the interaction term and window opening ($p = 0.95$).

6.7 Evaluation of perceived environment

The responses given in the questionnaires were evaluated to assess any relationships between actual environmental conditions and perceived environment and between perceived environment and window opening. Figure 6-12 and 6-13 show participants' evaluation of the environment they were exposed to.

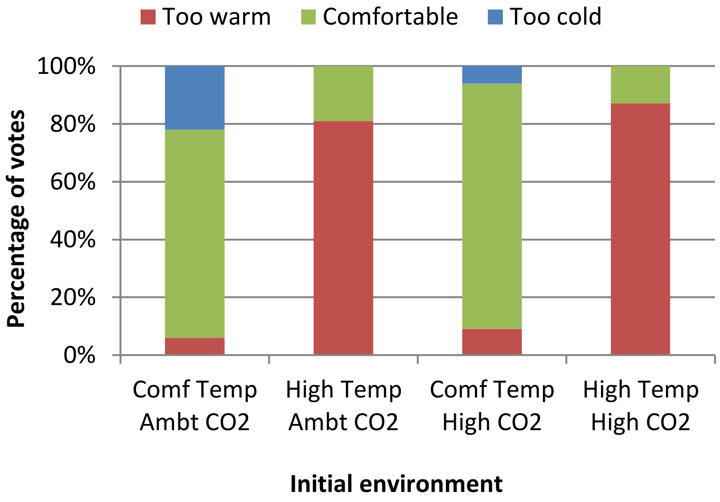


Figure 6-12: Participant's perceived thermal comfort in each temperature and CO_2 condition

To analyse the difference in thermal comfort evaluation between the environments, the "too cold" response was excluded as it only occurred in the comfortable temperature environments. None of the participants in the high temperature environment evaluated their thermal comfort as “too cold” and therefore no comparison can be made between the environments. The excluded responses were treated as missing cases in the analysis. Table 6-6 is the revised data used in the analysis

Table 6-6: Revised data for analysis of perceived environment

Total sample size	**128**
Missing cases	9
Total included in analysis	119 (93%)

Even with the cases removed, there was a clear difference in perceived thermal comfort between the comfortable and high temperature environments. In the comfortable temperature environments, an average of 78% of occupants evaluated their perceived thermal environment as “comfortable”. This value was 16% for participants in the high temperature environments. This difference in perceived thermal comfort between the comfortable and high temperature environments was statistically significant. The calculated χ^2 was 67.07 ($p < 0.001$).

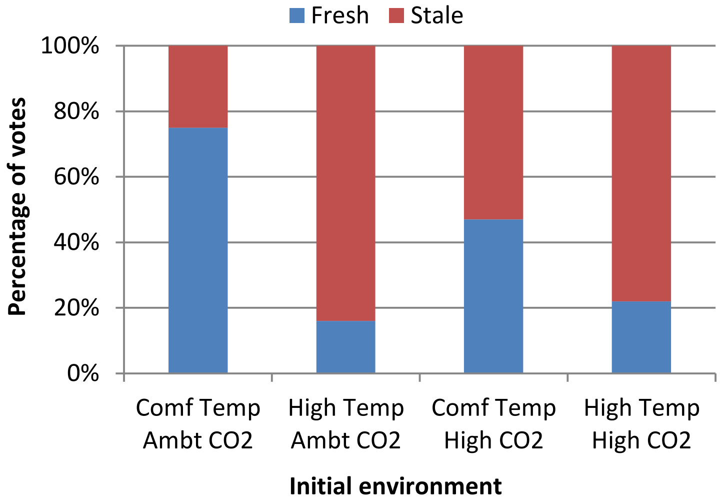


Figure 6-13: Participants’ perceived air quality in each temperature and CO_2 condition

The difference in perceived air quality (PAQ) between the environments was also examined using both temperature and CO_2 conditions. The analysis showed that temperature was associated with PAQ. The difference in perceived air quality between the comfortable and high temperature environments was significant ($\chi^2 = 23.76$, $p < 0.001$). The difference in perceived air quality between the ambient and high CO_2 conditions was not significant ($\chi^2 = 1.60$, $p = 0.21$). The effect of CO_2 was also investigated by assessing its effect in separate initial temperature conditions. The differences in the perceived air quality between comfortable temperature and high temperature environments were examined to determine the association between CO_2 condition and perceived air quality in different thermal conditions. The analysis showed that in the comfortable temperature environments, the difference in perceived air quality between ambient CO_2 and high CO_2 conditions was statistically significant ($\chi^2 = 5.32,\ p = 0.02$). This was however not observed in the high temperature environments ($\chi^2 = 0.41, p = 0.52$). These results imply that in high temperature environments the temperature effects seem to have the greatest impact on the perceived air quality. However, interestingly in comfortable temperature environments, CO_2 appears to have an effect on how occupants perceive the air quality.

The influence of the interaction between temperature and CO_2 conditions on perceived air quality was also examined. However, the interaction term did not have a significant effect on perceived air quality ($p = 0.052$). This result confirms that it is either temperature or CO_2 that influences perceived air quality.

Results from the questionnaires also showed that in high temperature environments, participants were more like to rate the air quality as stale compared to the comfortable temperature environments. This was regardless of the CO_2 condition. Figure 6-14 presents participants perceived air quality corresponding to their perceived thermal comfort. The blue bar represents the “Too cold” vote, the green bar represents the “Comfortable” vote and the red bar represents the “Too warm” vote. The solid section and the patterned sections of the bar represents the “Fresh” vote and “stale” votes for air quality. A statistical analysis of this observation showed that the difference in perceived air quality in the two thermal environments was significant ($\chi^2 = 11.21, p < 0.001$). This observation is similar to previous studies that showed that perception of fresh air improved as temperature and humidity decreased. This was regardless of the pollution content (Melikov & Kaczmarczyk 2012; Fang *et al.* 2004).

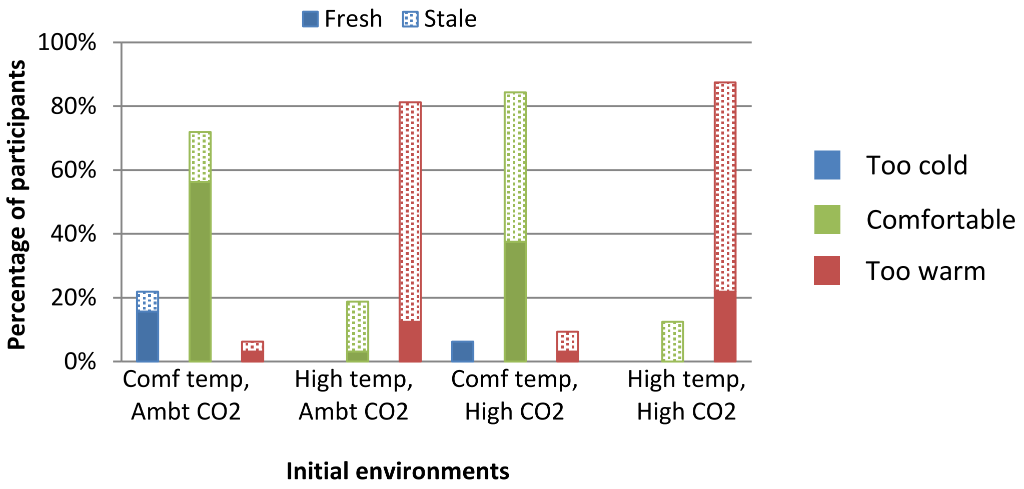


Figure 6-14: Perceived air quality corresponding to perceived thermal comfort in each temperature and CO_2 condition

A logistic regression analysis was conducted to examine the association between humidity and PAQ. The air quality votes were coded as “Fresh” = 1 and “Stale” = 2 (Table 6-4) and so the regression model predicted the probability of a “stale” vote. The model predicted that as humidity increases, the probability of a “stale” vote increases ($a = 3.15 \pm 0.83$, $b_{RH} = -0.07 \pm 0.02$), where a is the regression constant and b_{RH} is the regression coefficient for relative humidity. Statistical significance was observed at $p = 0.001$ however the regression coefficient was small, implying that its contribution to the model is small. Humidity could be used to explain 13% of the variance in PAQ between the thermal environments (Nagelkerke’s R^2 = 0.130). This result further supports Fang *et al.* (2004)and Melikov and Kaczmarczyk’s (2012) observation that PAQ improves at lower relative humidity.

6.7.1 Association between perceived environment and window opening

The association between participants’ perceived environment and their window opening behaviour was assessed to determine if occupants were using windows to control their environment according to their perception of their indoor environment. Figures 6-15 and 6-16 show the distinction of window opening between participants’ perceived thermal comfort and perceived air quality respectively.

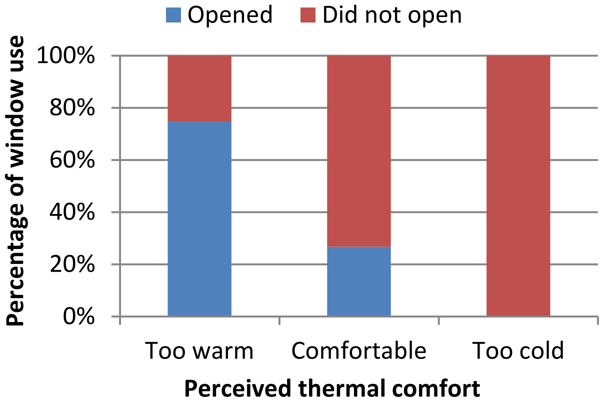


Figure 6-15: Participants window use due to perceived thermal comfort

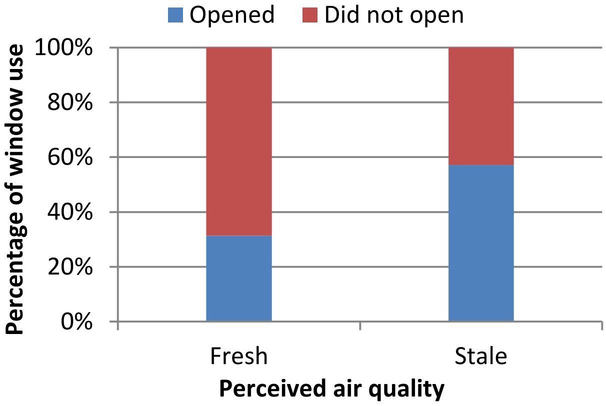


Figure 6-16: Participants window use due to perceived air quality

The statistical analysis showed a significant association with perceived environment and window opening. Occupants who evaluated the environment as “too warm” or “stale” were more likely to open a window compared to the “comfortable” or “fresh” evaluation. For perceived thermal comfort, the difference in window opening due to perceived thermal comfort was significant in all the environments ($\chi^2 = 24.96, p < 0.001$).

Due to the difference in perceived air quality in the different thermal environments, separate analysis was conducted to examine the association between participants’ evaluation and their window opening behaviour. In the comfortable temperature environment, a significant association was found between PAQ and window opening ($\chi^2 = 4.70,\ p = 0.04$). However, this was not the same for the high temperature environment ($\chi^2 = 3.44, p = 0.12$), implying that in the high temperature environments, other variables were associated with window opening. In this experiment, temperature and perceived thermal comfort were the dominant variables related to window opening in the high temperature environments. The results from the comfortable temperature environments indicates that when the participants were thermally comfortable but perceived the air quality as stale, they were more likely to open a window and that window opening in these environments were related to the CO_2 condition and the perceived air quality.

6.8 Reasons for window opening

Participants recorded their reasons for using the adaptive opportunities available to them. The reasons for opening the window were to improve thermal comfort, for fresh air or for a combination of both. The most significant reason for not opening the window was because the participant was comfortable or they wanted to get on with the work. The distribution of responses in each environment is presented in Table 6-7.

Table 6-7: Proportion of reasons given for window opening

Initial temperature	**Thermal comfort**	**Fresh air**	**Thermal comfort and fresh air**
Comfortable temperature Ambient CO_2	0%	83%	17%
High temperature Ambient CO_2	41%	36%	23%
Comfortable temperature High CO_2	13%	88%	0%
High temperature High CO_2	42%	29%	29%

In the comfortable temperature environment, the dominant reason given for window opening was for fresh air and in the high temperature environment the dominant reason was to improve thermal comfort. A combination of the need for improving thermal comfort and for fresh air was marginally higher in the high temperature environments compared to the comfortable temperature environments.

In the comfortable temperature environment, CO_2 was significantly associated with PAQ. When CO_2 was high, 53% of participants evaluated their air quality as stale. For these participants, it will make sense to open the window for fresh air rather for the other two reasons. In this environment, out of the participants who evaluated the air quality as stale, 41% opened the window. In high temperature environment, it was shown that temperature affects PAQ as well as thermal comfort. An average of 67% of participants in this environment evaluated their environment as too warm and stale. For these participants, it will make sense for the window to be opened to improve both thermal comfort and air quality.

6.9 Sensitivity analysis

A sensitivity analysis was conducted on the variables that were not controlled to assess their impact on the experiment methodology. The variables assessed were environmental (outdoor temperature, odour and external noise) and non-environmental (gender and geographic location origin).

6.9.1 Outdoor temperature

The association between outdoor temperature and window opening was examined to determine if outdoor temperature influenced participants' behaviour. In the binary logistic regression analysis, outdoor temperature was not a significant variable in the final model developed to predict window opening ($a = -0.88 \pm 0.62$, $b_{To} = 0.05 \pm 0.04$, $p = 0.24$) where a is the regression constant and b_{To} is the regression coefficient for outdoor temperature. Each defined environment was assessed in an individual analysis to examine any likely influence of outdoor temperature on window opening. Table 6-8 presents the regression parameters and the p values for each environment. There were no significant association between outdoor temperature and window opening in the conditions created for the experiment. This is largely due to the experimental conditions created for this study. The high indoor temperature conditions were extreme and hence the effects of indoor temperature had the greatest impact on window opening.

Table 6-8: Regression parameters for outdoor temperature

Initial environment	a	b_{To}	p
Comfortable temperature Ambient CO_2	-6.91±3.79	0.35±0.24	0.15
High temperature Ambient CO_2	0.83±1.48	0.01±0.10	0.94
Comfortable temperature High CO_2	-0.84±0.91	-0.02±0.76	0.76
High temperature High CO_2	1.48±1.69	-0.04±0.11	0.71

6.9.2 Odour

Participants recorded their perception of odour as “acceptable”, or “unacceptable”. Table 6-9 presents the proportions of perceived odour votes recorded in the questionnaires in each environment. The “unacceptable” vote was highest in the high temperature environments (13% in each) and the “acceptable” vote was highest in the comfortable temperature environment with the ambient CO_2 condition (97%).

Table 6-9: Proportion of perceived odour in each temperature and CO_2 condition

Initial environment	**Acceptable**	**Unacceptable**
Comfortable temperature Ambient CO_2	97%	3%
High temperature Ambient CO_2	88%	13%
Comfortable temperature High CO_2	91%	9%
High temperature High CO_2	88%	13%

A statistical analysis was conducted to assess the difference in perceived odour between the environments defined. The chi-squared test was used to assess the difference in perceived odour between the comfortable and the high temperature environments and between the ambient and high CO_2 concentration environments. An initial analysis showed that the difference in perceived odour in the four environments was not significant ($p = 0.46$). A further analysis of perceived odour in the thermal conditions and CO_2 conditions also did not show a significant difference (temperature: $\chi^2 = 1.47$, $p = 0.23$

and CO_2: $\chi^2 = 0.37,\ p = 0.54$). These results imply that participants evaluation of the odour in the office was not influenced by the initial environmental conditions created. The difference in perceived odour and window opening was also assessed. The difference observed was not significant ($\chi^2 = 0.14, p = 0.70$), implying that perceived odour did not have an impact on window opening when considering the full range of participants.

A further analysis was conducted to examine the relationship between relative humidity and perceived odour. In the binary logistic regression analysis, humidity was not a significant variable in predicting perceived acceptable odour ($a = 0.25 \pm 1.32,\ b_{RH} = -0.07 \pm 0.04,\ p = 0.07$) where a is the regression constant and b_{RH} is the regression coefficient for relative humidity.

6.9.3 External noise

The offices used for the experiment are in a building adjacent to a busy road. Spot measurements of sound levels were taken in the office (on the north façade) at three different positions and this was done twice in the day, with the window closed and opened. Table 6-10 presents the noise levels recorded in the office. Sound levels were measured in dBA. The recommended noise levels for office environments is between 30 and 45dBA (CIBSE 2006). The levels measured are higher than the recommended and as expected the levels were higher when the window was opened compared to when they were closed.

Table 6-10: Measured noise levels in test office

		Noise levels (dBA)			
Time	**Window state**	**Window**	**Desk (middle)**	**Door**	**Average**
10:00	Closed	52	47.5	50.0	49.8
	Opened	56.7	50.9	53.0	53.5
13:30	Closed	47.2	46.7	49.8	47.9
	Opened	64.7	55.3	53.5	57.8

Participants were asked to evaluate the external noise as “acceptable” or “distracting”. The proportion of participants that perceived the external noise as acceptable was 47% and for distracting it was 53%. From these proportions, 97% and 91% opened the window when perceived external was acceptable and distracting respectively. The difference observed between window opening and perceived sound was not statistically significant ($\chi^2 = 1.64$, $p = 0.28$). This implies that perceived external noise was not related to window opening. There was no difference in window opening when a participant evaluated the external noise as distracting compared to a participant who evaluated the external noise as acceptable.

6.9.4 Metabolic rate, age and gender

Attributes that relate to the occupant can play a role in prompting the occupant to interact with building systems including window use. Attributes that relate to the occupant include gender, age and activity level or metabolic rate. Previous studies in thermal comfort and preference have included an analysis of the possible difference between gender and age groups (e.g. Stenberg & Wall 1995; Indraganti & Rao 2010; Karjalainen 2007).

From the experiment conducted for this thesis, it was not possible to investigate the impact of different age groups on window opening. This is because, out of the 128 participants, only seven were not in the 20 – 29 age group, making it unreliable to compare the influence of the different age groups on the evaluation of the environment and also on window opening. However, age has been found to be related to thermal comfort. In their study, Indraganti and Rao (2010) found that age correlated weakly but significantly with thermal sensation, preference, acceptance and overall comfort. From their results, they found that overall thermal comfort rating was higher in their younger participants compared to the older participants. They also found that the older age group preferred a warmer environment compared to younger group and that the older participants were more tolerant of their thermal environment. This implies that the younger participants are more likely to adjust themselves or their environments to restore thermal comfort. Factors such as metabolic rate and activity levels should be considered when investigating the impact of age on thermal comfort and hence window use behaviour. The younger occupants may be more active compared to the older occupants.

Humans require energy to maintain the core body temperature and to perform work. The higher the activity level, the more heat is produced, i.e. the higher the metabolic rate, and when too much heat is produced through high levels of activities, sweating helps to cool the body in order to reduce the body temperature and increase thermal comfort. Behavioural actions such as adjusting clothing levels and opening a window can also be performed in an attempt to control thermal comfort. In an office where the type of activity performed is described as light manual work which is sedentary and corresponds to a low metabolic rate (ISO 8996 2009). However, activities performed just before arrival can have an impact on the occupant’s immediate behavioural actions. In the experiment conducted for this thesis, participants were asked about how they had arrived at the test building.

Over 90% of the participants said they had walked to the building and out of this, 31% worked in the building the experiment was conducted in and had been working at their desk before walking to the test office. The remainder had driven to the building. No higher level activities before participation (e.g. running or cycling) was recorded and so it was not possible to investigate the effect of metabolic rate on window opening behaviour and perceived environment.

Several studies have investigated the gender differences in thermal comfort and so far only small differences have been found (Beshir & Ramsey 1981; Muzi *et al.* 1998; Cena & De Dear 2001; Griefahn & Künemund 2001; Parsons 2002; Karjalainen 2007). These studies were conducted in both field surveys and climate chamber experiments. Fanger (1970) however did not find a significant difference in thermal preferences between the male and female participants in his controlled experiments. The results that have shown differences in genders imply that there may be a difference in how male and females control their environment to achieve thermal comfort. The influence of gender in the controlled experiment conducted for this thesis was further explored. The difference between genders in window opening, perceived thermal comfort and perceived air quality was assessed and presented in Section 6.9.4.1.

6.9.4.1 Gender

The majority of the participants were staff and students from the University of Sheffield. Due to the limited response rate for participation in the experiment, the number of male and female participants and participant country of origin were not controlled to ensure equal numbers in each environmental condition. Table 6-11 shows the distribution of participants by gender in each environment and Figure 6-18 shows the window use distribution for female and male participants. In this bar chart, the red bars represent female participants and the blue bars represent male participants. Although the proportions of male and female participants are not equal in each environment, Figure 6-17 shows that the proportion of participants who opened window and those who did not open windows are quite similar in both gender groups.

Table 6-11: Gender composition of participants in each defined environment

Initial environment	Male	Female
Comfortable temperature Ambient CO_2	21	11
High temperature Ambient CO_2	16	16
Comfortable temperature High CO_2	26	6
High temperature High CO_2	18	14
Total	81 (63%)	47 (37%)

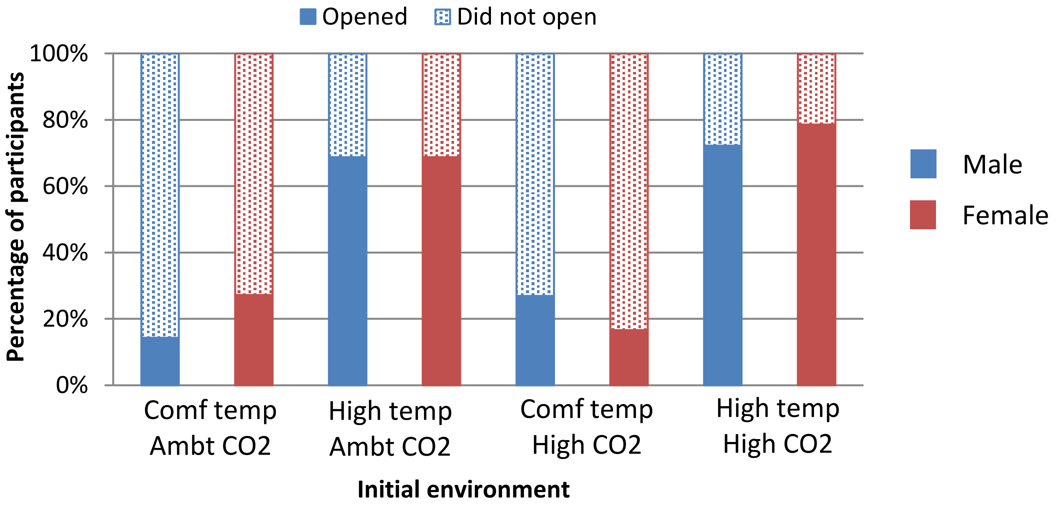


Figure 6-17: Proportion of window use between male and female participants (Blue bars = male; Red bars = female)

The difference in window opening in male and female participants was not statistically significant. Using the male gender as a reference variable, females were no more likely to open a window in any of the four environments as their male counterparts. Table 6-12 presents the χ^2 and the significance for each environment. In the high temperature ambient environment with ambient CO_2 conditions, equal number of male and female participants opened the window.

Table 6-12: Chi-squared and significance levels for differences in gender in window opening

Initial environment	χ^2	p
Comfortable temperature Ambient CO_2	0.80	0.39
High temperature Ambient CO_2	0	1
Comfortable temperature High CO_2	0.27	0.52
High temperature High CO_2	0.17	0.50

The difference in perceived environment between male and female participants was also investigated. Figures 6-18 and 6-19 show the variation in responses from male and female participants. The blue bars represent the males' responses and the red bars represent the females' responses. For the statistical analysis the "too cold" vote was not included as it was only observed in the male participants. No comparison could be made between male and female participants for this vote. There was no significant difference in perceived thermal comfort between male and female participants ($\chi^2 = 1.03,\ p = 0.35$). For the evaluation of air quality, the difference in response between male and females was statistically significant ($\chi^2 = 6.35,\ p = 0.02$). Female participants were 2.7 times more likely to say the indoor air was "stale" compared to the male participants across all the environments.

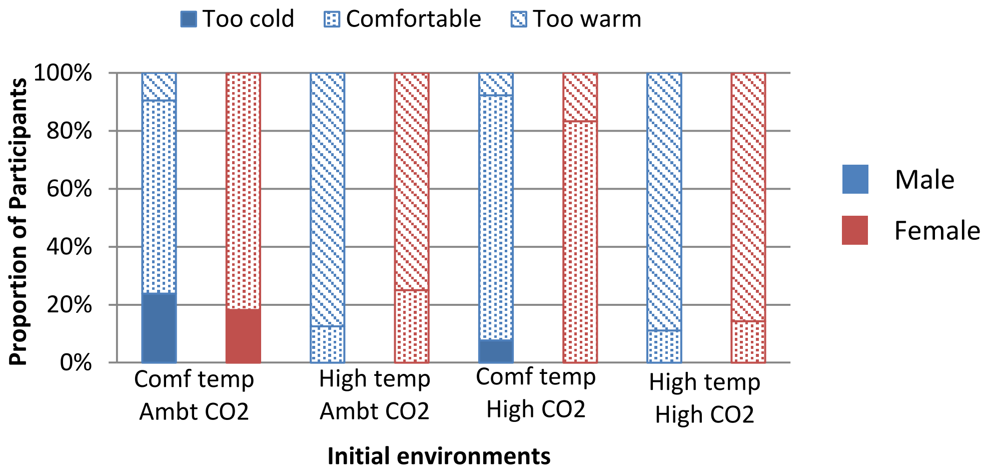


Figure 6-18: Variation in perceived thermal comfort between male and female participants in each temperature and CO_2 condition

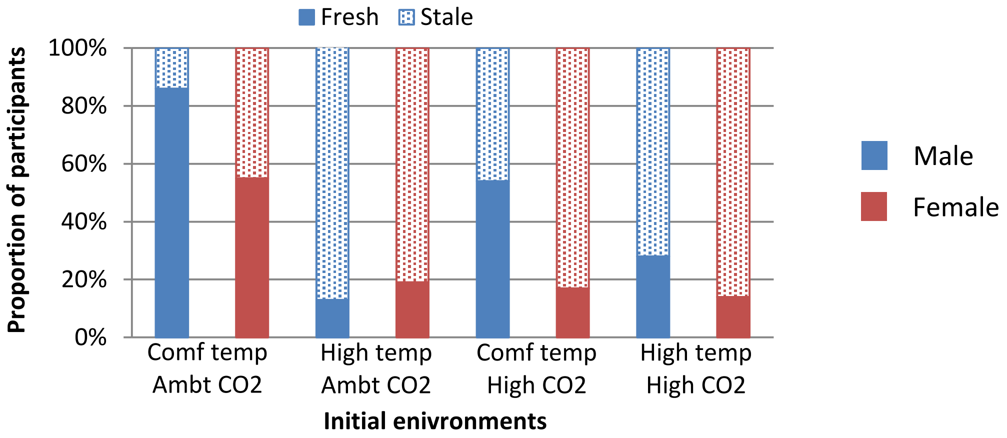


Figure 6-19: Variation in perceived air quality between male and female participants in each temperature and CO_2 condition

The difference between the proportion of male and female participants limits the generalisation of these observations. However they are in line with previous observations that the female gender is more sensitive to their indoor environment and perceived air quality (Stenberg & Wall 1995).

6.9.5 Geographic location origin

The distribution of geographic location origins of the participants in all four defined environments are presented in Table 6-13

Table 6-13: Distribution of geographic location origin of participants in each temperature and CO_2 condition

Initial environment	**UK**	**Europe**	**Africa**	**Asia**	**Americas**
Comfortable temperature Ambient CO_2	16	6	2	8	0
High temperature Ambient CO_2	17	2	3	10	0
Comfortable temperature High CO_2	15	2	4	10	1
High temperature High CO_2	10	4	3	14	1
Total	58 (45%)	14 (11%)	12 (9%)	42 (33%)	2 (2%)

Even though the proportions between the numbers of participants from the identified locations are not even, a binary logistic regression test was carried out to analyse any difference in window use and perceived environment between the locations. The United Kingdom was used as the reference location and the Americas location was omitted from analysis as there were only two participants from this location and both participants opened the window. The binary logistic regression showed that there was a statistically significant difference in window use between the locations ($\chi^2 = 10.34$, $p = 0.016$). This significant difference was only observed between the United Kingdom and Africa. Participants from Africa were less likely to open windows compared to participants from the UK. Table 6-14 presents the statistics for the locations. This observation could be because of the thermal history of participants from Africa as they may be used to warmer conditions compared to participants from Europe or Asia (majority of participants from Asia were Chinese). The amount of time participants from Africa had spent in the UK was not recorded and so further explanations cannot be given for this observation.

Table 6-14: Chi-squared and significance levels for the different locations compared to UK

Location	χ^2	p
Europe	3.84	0.05
Africa	4.60	0.04
Asia	1.93	0.76

The differences in participant perceived environment according to their geographic location was also tested. The difference in both perceived thermal comfort and air quality were not statistically significant. Participants from Europe, Africa or Asia were no more likely to evaluate their environment as “too warm” or “stale” compared to their counterparts from the United Kingdom.

6.10 Summary

An experiment with controlled conditions was conducted to investigate the influence of CO_2 concentration on window opening during the arrival period. This study demonstrates the use of an experiment to observe window opening behaviour. Initial temperature and CO_2 conditions were created and the high temperature and high CO_2 conditions were selected to force window opening. The thermal environment defined as comfortable was selected in order to examine occupant’s window opening behaviour in response to different levels of CO_2 concentration. The observation showed that more occupants in the high temperature environments opened the window compared to occupants in the comfortable temperature environments and the difference between these environments were statistically significant. However, in the ambient and high CO_2 environments, the difference observed in window opening was not significant, implying that CO_2 concentration was not a driver for window opening during the arrival period.

Analysis of the participants’ responses in the questionnaires indicated that there was a difference in perceived environment between the initial environments. In the comfortable and high temperature environments, perceived thermal comfort was influenced by temperature. In the high temperature environments, perceived air quality was also influenced by temperature. In the comfortable temperature environment however, perceived air quality was linked with CO_2 concentration. These results indicate that in thermally uncomfortable environments, temperature may have a suppressor effect on CO_2 concentration and will have the greatest impact on both window opening and perceived environment. Whereas in thermally comfortable environments, CO_2 concentration may begin to have an effect perceived air quality which can result in window opening.

The experiment conducted for this thesis successfully controlled the known environmental factors which were initial temperature and CO_2 conditions while other environmental variables (e.g. weather, indoor relative humidity and indoor air pollutants) and non-environmental factors (e.g. gender and geographic location origin) were not controlled. As participants were blinded to the experimental conditions, the impacts of the uncontrolled variables were thought to be unlikely. The results from the sensitivity analysis showed that in this experiment, outdoor temperature, odour, external noise and gender did not impact on window opening. A statistically significant difference in window opening between participants from who were from Africa and participants from the UK was however observed. Although significance was observed, the difference in proportions of participants from the identified locations was not controlled and so these results cannot be generalised.

Since indoor temperature and CO_2 concentration were the parameters of interest, the results provide validation for the experiment methodology because a significant percentage of the participants responded to the high indoor temperatures and they adapted their environment by opening a window. It is however acknowledged that further observations with equal gender representation and geographic location representation are required draw further conclusions. As well as these, occupant activity prior to the start of the experiment should be recorded and its possible influence on the outcome assessed.

7 Discussion

7.1 Introduction

In the following sections, the drivers for window opening are discussed through a comparison of survey methods and results, from both earlier studies and the current study. Chapter 2 demonstrated the variability in results from earlier studies. One possible reason for this is the type of survey method used. Clearly if different methods provide different results then this has implications for the suitability of models developed. Therefore in this section the role of survey method will be investigated using the results from this study and those by previous authors.

7.2 Comparison of methods

In order to assess the effect different methods have on the model results it is useful to compare the results from two different methods studying window use under the same conditions (same buildings, occupants and similar weather conditions). Chapter 4 and 5 presented results from the photographic survey and the indoor survey that allow this comparison. Both survey methods have been used previously to investigate factors that influence window use. However, this is the first time both survey types have been used in the same location, on the same buildings and in the same weather conditions. This means that the observations can be compared to assess the variations in the results. In both surveys, the probability of a window being in the open state can be inferred from the measured weather conditions and time of day variation in windows open can also be assessed. In addition to these, the probability of windows changing state due to the measured variables can be assessed. The first limitation to consider here is the possible difference in time steps between observations. Depending on the frequency of which the building façades are photographed, the time steps may be considerable greater than in the indoor survey where data loggers capture every window state change as it happens.

In the current project, separate but comparable analyses were carried out on the observations made in both surveys using logistic regression methods. For logistic regression, the larger the sample size the better the probabilistic model fits the observed data. In the photographic survey, the states of a significant number of windows were observed for each measured value of a given weather parameter and in the indoor survey, window states at all measurements of each environmental parameter was recorded. Both surveys were conducted over a period of time and across three seasons in order to observe the effect of the variation in environmental conditions due to seasonal changes. This resulted in a sufficient amount of data which could be analysed using logistic regression.

For the analysis, only the influence of weather conditions on windows open was assessed for the observations made in the photographic survey. In the indoor survey, both indoor environmental conditions and weather conditions were assessed. In univariate analysis, indoor and outdoor temperatures were individually found to be significant predictors of windows being in the open state. Both results are in line with earlier studies that observed windows open using these methods. However, there is greater variation in the results obtained from the two different methods compared to results from studies that used the same method. In other words the variation in predictions from observation in two separate indoor surveys is less than the variation in predictions from an indoor survey and a photographic survey. A comparison of results from observations made from the different survey methods will be presented followed by a comparison of the results from the same survey methods.

The idea that the photographic survey does not have an effect on occupant behaviour is an advantage. Occupants are not aware that they are being observed which can otherwise influence them to change their behaviour. In the indoor survey occupants are aware of the data loggers in their offices and so they may be inclined to alter their behaviour. This advantage of the photographic survey may imply that this survey method is a better representation of window use behaviour in a building. However, the frequency of observation is an important factor to ensure that sufficient amount of information is obtained before a conclusion is drawn.

Figure 7-1 is a comparison of the regression curves as a function of outdoor temperature observed in the photographic and indoor surveys presented in Chapter 4 and 5 respectively. The curves have been plotted over the range of outdoor temperatures measured during the survey period. It can be seen that the photographic survey predicts much lower probabilities of windows open compared to the indoor survey. The regression coefficient for outdoor temperature for the indoor survey model ($b_{Tout} = 0.20 \pm 0.0003$) was greater than that of the photographic survey model ($b_{Tout} = 0.13 \pm 0.001$). The lower standard error of the indoor survey coefficient indicates that the probability of windows being in the open state is more sensitive to a change in outdoor temperature compared to the photographic survey model. In the indoor survey, since measurements are recorded continuously, window state at each occurring outdoor temperature is known. This gives confidence that the model fits well with the observation. The lower predictions from the photographic survey could be due to the frequency of taking photographs. Information on window use between the times of observation will be missed. This may be an even bigger issue if there are significant changes in weather conditions, such as rain, occurring between observation times. In the indoor survey, window states are continuously recorded hence the information from this survey is more detailed and informative.

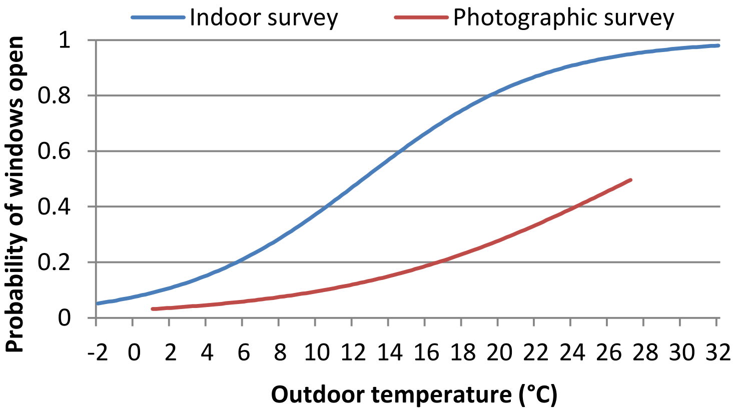


Figure 7-1: Comparison between results from the indoor survey and the photographic survey conducted in the current study: Probability of windows open as a function of outdoor temperature

Figure 7-2 and 7-3 compare the regression curves from observations made in photographic surveys and observations made in indoor surveys by other authors respectively. Figure 7-2 shows the predicted probabilities of window open as a function of outdoor temperature estimated from the current photographic survey and a photographic survey conducted by Zhang and Barrett (2012). It confirms that the photographic survey predicts much lower probabilities of windows open. However, the differences between the current survey and Zhang and Barrett's survey should be considered as well. Both surveys were conducted on the same building. Since the earlier study, the building has undergone a major refurbishment (details presented in Section 3.2.2). The other difference to consider is the frequency of and duration of the observations. In the current photographic survey, observations were made four times a day for a minimum of 10 days in the summer, autumn and winter and in the earlier survey, the façades of the building were photographed twice daily for a whole academic year (not including summer). This raises the question about the survey methodology. Is it better to take the same measurements less frequently but over an extended period of time or more frequently over a short period of time? By comparing the results from the current photographic survey to previous study, it can be seen that less frequent observations of window states does underestimate the probabilities of window open and this is regardless of the of long the survey is conducted for and the amount of data collected.

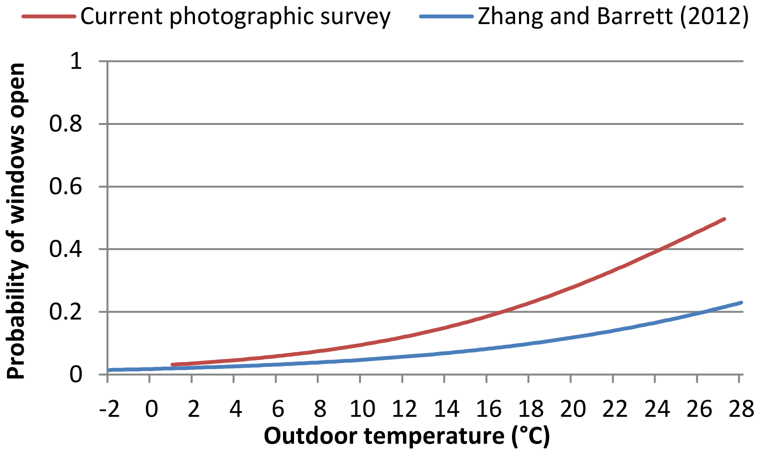


Figure 7-2: Models of probability of window open as function of outdoor temperature from photographic surveys conducted in the current study and by Zhang and Barrett (2012)

In Figure 7-3, the regression curves for the observations from indoor surveys are presented. The curves are plotted over the range of the outdoor temperature measured during each survey. The differences in the earlier study and the current study are the location, the survey duration, the sample size and the range of environmental conditions measured. The details of the differences are presented in Table 7-1. The predictions from the current observation are higher than that from the observations made in the earlier study. In both studies, the regression curve for outdoor temperature was a much better fit compared to the curve for indoor temperature and outdoor temperature explained a bigger proportion of the variation in observation compared to the other variables measured. In the current survey, outdoor temperature accounted for 29.6% of the variation and in the earlier study it accounted for 24.7% of the variation. Outdoor temperature was the best predictor of windows open. The variation in the models however confirms the findings of Nicol (2001) who showed that UK office workers were more likely to open windows compared to their counterparts in other European countries. Aside from the possible influence of other environmental variables (e.g. difference in indoor and outdoor temperature), another reason could be the differences in occupant parameters. Personal preference and cultural differences due to the country of origin may influence occupant window opening behaviour.

Although there is still a difference in the results from each study, it is clear that if you compare Figure 7-2 to Figure 7-1 the difference between the two indoor surveys is much reduced compared to the difference between an indoor survey and a photographic survey.

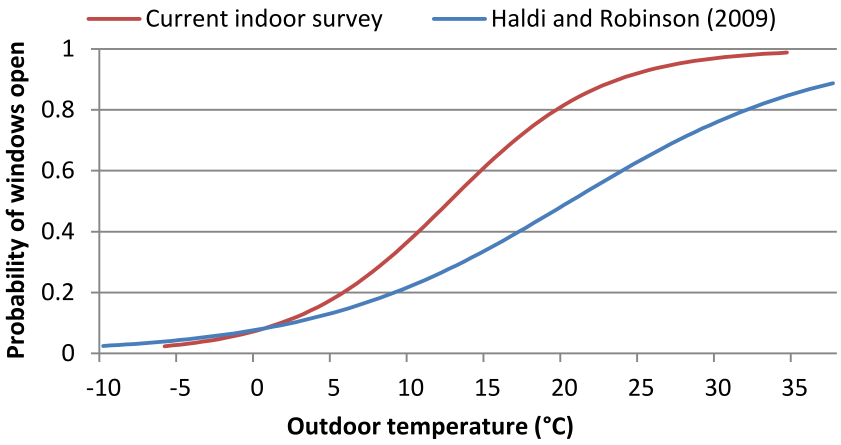


Figure 7-3: Models of probability of windows open as a function of indoor temperature from observations from indoor surveys conducted in the current study and by Haldi and Robinson (2009)

Table 7-1: Comparison between earlier study and current study

Study features	**Current indoor survey**	**Haldi and Robinson (2009)**
Location	UK	Switzerland
Duration	8 months (covering summer, autumn and winter)	7 years
Sample size	7 single person offices	8 single person offices and 6 two person offices
Outdoor temperature range	-2.1°C to 34.8°C	-9.7°C to 37.1°C
Indoor temperature range	9.8°C to 34.8°C	13.8°C to 31.1°C

The probability of windows open as a function of indoor temperature observed in the current study and in Haldi and Robinson's (2009) study is also presented in Figure 7-4. In both studies, indoor temperature was a significant predictor of windows open. In the current study, indoor temperature explained 5.1% of the variation in the observed data and in the earlier study it explained 4.6% of the variation. In both studies, the model for indoor temperature does not fit the observed data as well as the model for outdoor temperature. However, the variation in the prediction from both studies is not as great as the predictions due to outdoor temperature.

In the current indoor survey, CO_2 concentration was also measured and its influence on windows open was assessed. For the analysis, CO_2 was a significant predictor of windows open and it explained 6.5% of the variation in windows open. The influence of CO_2 concentration observed in the current study will be discussed in more detail later. In the earlier study, CO_2 concentration was not measured. This raises the issue of how studies and the results obtained may be limited by the variables measured. Different results are obtained due to the variables that are measured and assessed.

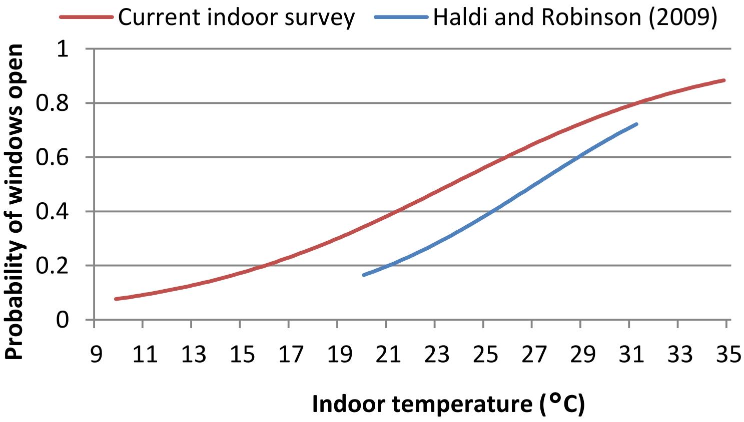


Figure 7-4: Models from observations from indoor surveys conducted in an earlier study and in the current study: Probability of windows open as a function of indoor temperature

The variation observed in the predictions shown in Figures 7-3 and 7-4 also raises the question about survey methodology. Is it better or is there an advantage in conducting a survey over an extended period of time or will a shorter survey be sufficient to capture the occupant behaviour that will be representative of the population in the building? Also, which variables are the most appropriate or realistic to consider when investigating factors that influence window opening? The variation in results due to differences in survey method has been experienced in the thermal comfort surveys which were conducted to specify acceptable indoor temperature (ASHRAE 2010a; CEN 2007b) (discussed in Section 2.2.1). The variation in the comfort temperature range was attributed to differences in the survey methods, buildings used in the survey and even differences in the research teams and instrumentation used.

From the different studies, different parameters have been found for predicting windows open. Variations in the models are due to the survey methodology (survey type, observation frequency and duration, variables measured), the building location and the window type. These variables are therefore important to consider when investigating window opening behaviour. In order to validate the model generated from one survey, the model should be applied to similar buildings to assess the accuracy of the predictions of probabilities of windows open.

7.3 Time dependent variation

Observations in the current study confirmed the time of day differences in window opening reported in earlier studies (Yun & Steemers 2008; Herkel *et al.* 2008; Haldi & Robinson 2009). It was observed that window opening occurred mostly on arrival compared to the intermittent period and at departure. In an indoor survey, the exact time of window opening is recorded and occupancy patterns can be determined using motion sensors or state loggers mounted on the door to record first entry into the office and last departure from the office. This makes the indoor survey a suitable survey to observe time of day variation in window use unlike the photographic survey where details on occupancy are not available. The probability for a window state changing from closed to open can be calculated using the measured parameters that occur just before the state change event. This study has confirmed that window use behaviour depending on whether it is the arrival period, intermediate period or departure period. Further, it has shown that the relative importance of the environmental variables alters depending on the time of day, with indoor and outdoor temperature being significant on arrival and indoor temperature and CO_2 having significance during the intermittent period. Therefore, it seems essential that any future study is designed in such a way as to allow consideration of the three periods.

7.3.1 Window opening on arrival

In their study, Yun and Steemers (2008) only measured thermal conditions and they did not find outdoor temperature as a significant predictor of window state changing from closed to open. Hence for the arrival period, indoor temperature was the only predictor of window opening. Figure 7-5 is a comparison of the resulting regression curve from Yun and Steemers (2008) and from the current survey. Both surveys were conducted in different locations within the UK however the earlier study was only conducted over the summer season whilst the current study is extended over autumn and winter.

The first observation here is the difference between the plot with all the data (Figure 7-4) and the arrival period only plot (Figure 7-5). Dividing the observations into the different time periods give a different shape even though the same variable is used to predict the probabilities of window opening. In both studies, the regression curves show that in the offices with night ventilation, the probabilities of window opening increases sharply with increasing temperature until it reaches 1.0, at approximately 26°C. For the office without night ventilation, the increase is less sharp. The variation in the observations could be due to the difference in location or the role of other environmental conditions. However, another consideration for this comparison is that Yun and Steemers (2008) regression curve for night ventilation is from observations made in one office over a summer season. In the survey, they observed six offices however, five were offices without night ventilation and one was with night ventilation and they analysed the data separately. All the offices observed in the current survey were able to utilise night ventilation which was employed during the survey period. From the observations at departure, 24% of departure window events remained opened.

Yun and Steemers also reported that occupant perceived control played a role in window opening. Occupants in the offices without night ventilation were less likely to open a window when they felt that they had little control over the thermal environment and so opening a window was not effective in improving the environment.

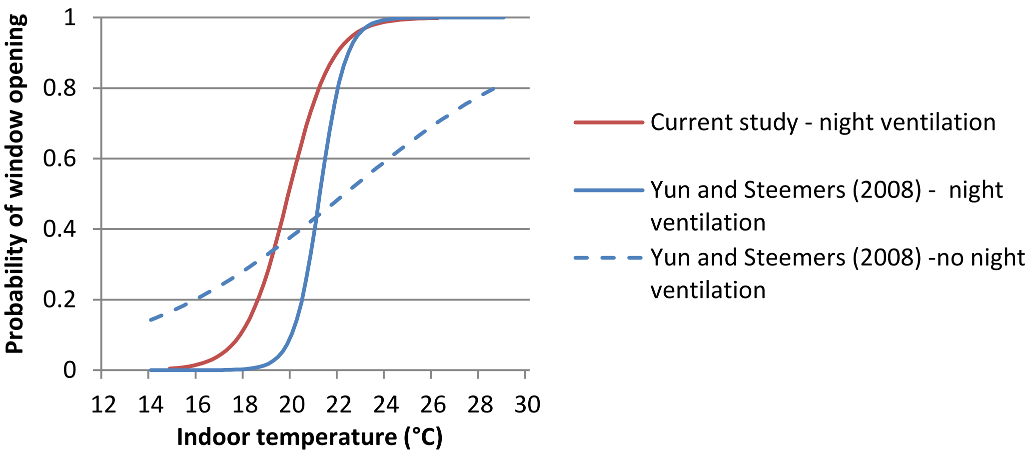


Figure 7-5: Models of probability of window states changing from closed to open on arrival as a function of indoor temperature from the current study and from Yun and Steemers (2008).

In the current indoor survey, a multivariate analysis showed that multiple variables were significant predictors of window opening on arrival. This was similar to the results obtained by Haldi and Robinson (2009). In both studies, indoor and outdoor temperatures significantly predicted window opening, however, from the observation made in the current indoor survey there were differences in the role of outdoor temperature in the model. From the earlier study, the probability of window opening increased with increasing indoor and outdoor temperature and in the current study, the probability increased with increasing indoor temperature and decreasing outdoor temperature. Since seasonal variations in window use was observed in the current photographic survey, a season-specific analysis was conducted to further explain the observation on arrival. The results presented in Section 5.8.1 show that the variation in the results can be due to the seasonal effects, resulting in the different models.

Through dividing the data into different time periods and then different seasons, a greater understanding of the window opening behaviour is found with different predictive models developed for the different times. This demonstrates the importance of the chosen analysis on the results generated.

CO_2 concentration was measured in the indoor survey however it was not shown to predict window opening on arrival. One possible reason for this is that high CO_2 levels were not present during arrival in the current indoor survey. Further detailed investigation of the role of CO_2 on window opening under experimental conditions showed that occupants were not likely to open their windows due to high (3000ppm) when spending a short time (30 minutes) in an office.

7.3.2 Window opening during intermittent period

For window opening during the intermittent period, Yun and Steemers (2008) did not observe any window opening in the office with night ventilation during the intermittent period. Once a window had been closed, it remained closed for the rest of the day. This either suggests a successful application of night ventilation in providing sufficient cooling during the day without opening a window or a possible consequence of the small sample size and/or the short observation period. If night ventilation was effective in providing cooling during the day then facade design or night ventilation may have an impact on window opening behaviour hence different probabilistic models can be obtained for different building designs. However, this comparison will only be possible if comparable survey methods are used to generate the models.

In the current indoor survey and in Haldi and Robinson's (2009) study, window opening was observed during the intermittent periods however different predictors were found to predict window opening during this period. Alongside indoor temperature, Haldi and Robinson (2009) found outdoor temperature to predict window opening but this was not the case in the current indoor survey due to the seasonal effects.

Yun and Steemers (2008) suggested that occupant window opening behaviour was a response to the particular environment they were in. Indoor temperature is affected by factors such as the weather and façade orientation and hence there could be a variation in indoor temperatures in different offices in the same building. It therefore makes sense to assess indoor temperature as a predictor of window opening rather than outdoor temperature. During the intermittent period, occupants may have been in their office for a period of time and hence they would be responding to changes in the indoor temperature unlike the arrival period where their experience of the immediately preceding outdoor thermal conditions may have an impact on their response when they enter the indoor space. This could be the reason why outdoor temperature was no longer a significant predictor of window opening during the intermittent period.

One difference between these studies is that in the current survey CO_2 concentration was also measured and in the previous study it was not. In the current study, indoor temperature and CO_2 were the significant predictors of window opening and in the season-specific analysis it was shown that CO_2 was only significant in the autumn and winter and not the summer.

The experiment conducted for the arrival period was complemented with questionnaires and occupants' responses showed that the thermal environment and the CO_2 levels affected perceived environment. Participants showed a perception of air freshness in the lower temperature environments and this was regardless of the CO_2 level. In the low temperature environments, when occupants perceived stuffiness, it was significantly linked to CO_2 concentration indicating that occupants can sometimes sense CO_2 concentration in some ways. The results also showed that perceived environment affected window opening.

This provides confidence in the role of CO_2 on window opening in the intermittent environment, as it shows that CO_2 is perceived by some people, and when it is perceived it does prompt window opening. It may be that this is not a strong enough effect for people to open windows when they are only in a room for a short period of time. Alternatively, in the indoor survey there may have been a combined increase in smell (due to body odour) with the increase in CO_2 which was not measured.

The time of day and the season-specific results highlight the further differences in occupant window opening behaviour. Window opening studies should not ignore the time of day and seasonal variations as these can have important implications on the results. As well as this, the inclusion of CO_2 concentration has shown that this variable influences window opening. It might be beneficial to further include other environmental parameters as they might significantly predict window opening.

7.4 Summary

A comparison of the various probabilistic models shows that there are variations in the predicted probabilities of windows open and window opening. This is an indication that other variables may have a role in occupant window opening behaviour. As well as this, the survey method, sample size, survey duration and frequency of observation also results in variations on the predicted probabilities. There is currently no standard methodology for investigating factors that influence window opening behaviour. The available probabilistic models provide parameters for predicting window opening due to thermal conditions and time of day occupancy periods. They also provide some parameters for location-specific, building-specific, window type and opening-specific predictions. Findings from the current survey have also shown the implication of considering seasonal changes at the different time periods, CO_2 concentration and occupant's perceived environment on window opening.

The experiment with controlled conditions demonstrates a new method for investigating occupant window opening behaviour in thermally comfortable environments. The significant influence of indoor temperature was in-line with results from field observations and occupants' perceived environments corresponding to the environments created were also in-line with observation made in earlier studies. These show that the experiment was effective in achieving its objectives.

In order to increase the accuracy of the predictions, further observations in both field surveys and experiments are required to confirm some of the known parameters (e.g. buildings with night ventilation, influence of CO_2 concentration in thermally comfortable environments, occupant perceived environment) and to specify the influence of unknown parameters (e.g. indoor air pollutants, window opening types, external noise, perceived control, occupant preference and multiple occupancy rooms). Occupant parameters are stochastic in nature and will result in variations in the models. This makes it important to consider how practical and realistic probabilistic models with multiple independent variables (some of which are stochastic) are.

8 Conclusions and further work

8.1 Conclusions

8.2 Recommendations for further work

8.1 Conclusions

This thesis aimed to extend the understanding of the factors that influence occupant window opening. Through the literature review it was shown that although current window use models exist, the parameters influencing this is limited and there is a large amount of variation between models. This highlighted the need to further investigate window use, investigating the influencing factors that may result in different models: methodology, time of day and season. Further, it was necessary to incorporate a wider range of variables that may influence window use, and CO_2 was highlighted as an important parameter to investigate. The findings for each key objective are outlined below.

1. **Identify the environmental factors that are correlated with window open state**

The current results confirm that indoor and outdoor temperatures are the main predictors of windows open and they account for the greatest proportion of the variation in the observation. Using the logistic regression method, the model for outdoor temperature was a much better fit of the data compared to the model for indoor temperature. Other environmental factors found to influence window open state were wind speed and outdoor relative humidity. However, variation between previous studies highlighted that the significance of different variables varies between studies and it is therefore necessary to investigate further this difference.

2. **Compare window opening predictions determined by using different field survey methods**

The comparison of window opening models was conducted to examine the implication of field survey methods on window opening predictions. Comparing results from observations made from an indoor survey and observations from a photographic survey, it was shown that the photographic survey predicts lower window use than the indoor survey. Even though a photographic survey studies a greater number of windows, and even when it is over an extended period of time, the predictions from the resulting model was much lower than that from an indoor survey.

This may be due to the reduced frequency of observations in the photographic survey. The length of survey and the range of outdoor conditions and season (and hence heating scenario) also impacted on the predictive models generated. For instance, a survey conducted over a summer season would only record window opening behaviour based on a limited range of outdoor temperature, and would not collect information on the different behaviour in winter.

Importantly different studies using a similar method on different buildings showed more similar results, than studies using the same building with a different method. This indicates that the methodology is an important factor that affects the final predictive model. It is therefore not possible to compare results generated with differing methods. Therefore, in order to generate a data base of window opening behaviour across a range of building types and locations it is necessary that a common robust methodology is used.

3. **Identify environmental factors that influence window opening in different periods of the day and in different seasons and develop appropriate predictive models for window opening**

In order to investigate the factors associated with window opening a further study was carried out determining the factors that predict window state changing from closed to open. This is useful as it considers what the occupants respond to in order to open a window to adjust or improve their environment (rather than the simple correlating the internal conditions to the window position at that time). The role of season and time of day on window opening behaviour was investigated. The results from this analysis showed a difference in significant predictors of window opening at the different periods. The combination of predictors which were found to be significant for the arrival period were different from the combination found to be significant during the intermittent period. In the current study, CO_2 concentration was measured and its influence on window opening assessed. This is the first time CO_2 concentration as a predictor of window opening has been investigated in an office building. The results showed that during the intermittent period, CO_2, alongside indoor temperature, is a significant predictor of window opening. However, this was only observed in the autumn and winter seasons. The final significant predictors for different time of day and seasons are shown in Table 8-1.

Table 8-1: Significant predictors of window opening at different time periods and in different seasons.

Time of day	**Season**	**Indoor temperature**	**Outdoor temperature**	**CO_2 concentration**
Arrival	Summer	✓	✓	
	Autumn		✓*	
	Winter	✓	✓*	
Intermittent	Summer	✓		
	Autumn	✓		✓
	Winter	✓		✓
Departure	Summer		✓	✓

* indicates a negative correlation

4. Compare the relative importance of indoor temperature and CO_2 concentration on window opening

Following on from the time of day analysis, the relative importance of CO_2 concentration in a low temperature condition was investigated. The previous results did not show a significant effect of CO_2 in the arrival period. However, this may have been because the conditions did not exist. It is difficult in field surveys to study a significant number of occurrences of high CO_2 without the influence of high temperature. Therefore, this was conducted in an experiment to observe whether short term exposure (representing the arrival) to high CO_2 levels would prompt occupants to open windows. The results showed that even in high CO_2 conditions occupants in thermally comfortable environments were less likely to open a window compared to occupants in thermally uncomfortable environments. The interesting finding from this experiment was that in the low temperature environments, some experiment participants perceived stuffiness and this was significantly attributed to the CO_2 level. Perceived environment was also linked to window opening and hence when participants were able to sense CO_2 concentration, they were more likely to open a window. However, this was only a small number of participants.

This study provides reliable evidence that window opening behaviour is influenced by multiple parameters. The variation in window opening due to time of day and seasonal changes and the addition of CO_2 concentration as a significant predictor of window opening in the intermittent period is a useful and novel finding for the prediction of occupant behaviour.

8.2 Recommendations for further work

What remains to be addressed is the generality of the resulting models. It will be useful to validate the window opening models by applying them to different buildings in order to assess their accuracy in predicting occupant window opening behaviour.

Due to the seasonal variation in window opening, further field observations should be conducted to include measurements in the spring season and any variation, particularly between the spring and autumn seasons should be assessed. Environmental factors such as solar gain and mean radiant temperature should be included in the possible factors that influence window opening as their impact on the indoor thermal conditions may vary in different seasons.

In the indoor survey, a useful observation to record would be occupancy patterns to show when the office is occupied and also the number of occupants. This will be useful for the intermittent period to assess the nature of the role of the significant predictors and if occupants adapt after long periods of occupancy or short-term exposure to the environmental conditions.

The comparison of the methods showed that the indoor survey is the most appropriate method as it gives much more detailed information on windows open at the corresponding measured variables, it shows the exact time a window states is changed and it also shows the variation of window opening in the day. Future surveys of occupant window opening behaviour should employ this method and additional environmental factors such as external noise and other indoor air pollutants should be investigated to extend the knowledge of variables that predict window opening. Subjective responses from occupants can also be recorded to further investigate the impact of perceived environment and perceived control on window opening.

As an alternative to a field survey an experiment provides the opportunity to study the impact of very specific conditions, and also to remove the overriding effect of temperature which can occur in the real environment. This enables a more detailed study of how people use windows in thermally comfortable environments. However, it is important to note how window behaviour is different at different times of day, therefore future work with experiments should consider the participants being in the office for much longer periods perhaps a whole day. It may be more useful to encourage participants to come to a room with controlled conditions to carry out their usual work. However, this can result in ethical issues if you are deliberately creating conditions where you know the occupant is likely to have a reduced performance. Non-environmental factors such as occupant age, activity levels and metabolic rates should also be considered in order to assess their influence on window opening behaviour.

To improve the prediction of occupant behaviour, additional surveys which include the measurements of multiple parameters will be required to collect more data on window opening. A useful and significant work would be to classify window opening behaviour according to location, building type, window type and opening type, season, indoor and outdoor climate, time of day, indoor air quality, occupant type (active/passive) and occupant preferences. The models should be validated to ensure that the appropriate model is applied to predict window opening behaviour. This will require deciding on a standard method for investigating window opening behaviour, collecting more data to include a wider range of parameters relating to the environment, the building and the occupant and applying the models to different buildings to assess the resulting predictions.

Knowledge gained from the recommendations presented will further enhance the findings of the current study and also improve the representation of occupant behaviour in building simulation and in design. Recently, efforts have been made to demonstrate the integration of occupancy models in multi-agent simulation in an attempt to improve predicted building performance (Chapman *et al.* 2014). Haldi and Robinson's (2009) window opening model was used to predict window actions and the energy required to heat a building was estimated. The initial results showed considerable differences between the predicted and the determined heating demand. A significant proportion of the variation in the results was attributed to the window model as it lacked the influence of relative humidity and air quality parameters. A standard survey method to investigate occupant window opening behaviour and a wider range of window opening predictors will contribute towards improving such promising efforts in building simulation.

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Appendices

The following is a list of publications related to the work in this thesis. 1 and 2 are directly related to the current work and 3 was published using some of the data collected in the field survey.

1. Bruce-Konuah, A., Hathway, A., Fotios, S. (2012). Window use in single person offices: do occupants control personal ventilation to provide adequate IAQ? *Proceedings of Healthy Buildings*. Brisbane, Australia.
2. Bruce-Konuah, A., Hathway, A., Fotios, S. The influence of carbon dioxide concentration on window opening behaviour: An experimental study. (In preparation)
3. Hathway, A., Papakonstantis, I., Bruce-Konuah, A. Brevis, W. (2014). Towards understanding the role of human activity on indoor air flows: A case study of door motion based on both field and experimental activities. *Proceedings of Indoor Air*. Hong Kong.

Window use in single person offices: do occupants control personal ventilation to provide adequate IAQ?

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SUMMARY

Tests with participants in controlled environments similar to a single person office have been designed in order to evaluate the relative importance of indoor temperature and carbon dioxide (CO_2) on the use of windows to provide acceptable indoor air quality (IAQ). Alongside observations of adaptive behaviour, questionnaires are used to establish why adaption did, or did not take place and record participant subjective assessment of the indoor environment. This paper presents results from the experiment. The results obtained indicate that indoor temperature has a significant effect on occupant window use behaviour, in line with previous field studies on window behaviour. Interestingly, at comfortable indoor temperatures and high CO_2, occupants did not open windows even though they reported that the environment felt stuffy. This indicates there are issues with assuming occupants will react to high CO2levels and control their own air quality given good quality thermal comfort.

KEYWORDS: CO_2, temperature, indoor air quality, occupant behaviour, windows

1. INTRODUCTION

Buildings use a significant amount of energy. Domestic and services energy use account for approximately 36% of total energy consumption respectively (EEA, 2011). Space heating accounts for more than half of the energy used in domestic buildings. Of the total amount of energy used, as much as 50% is lost through the departing air stream (Liddament and Orme, 1998). In the UK about 36% of carbon emissions come from buildings (CCC, 2010). Improving the energy efficiency of buildings is essential in order to meet targets for emission reduction. The building sector represents a substantial energy saving and emissions reduction potential. To realise this potential, it makes sense to reduce the amount of energy lost from buildings through improvement in insulation and airtightness, reducing air infiltration.

Reduced infiltration will lead to greater dependency on appropriate ventilation design to provide adequate ventilation and IAQ. The recommended ventilation rate for non-residential buildings is 10 L/s per person (prEN 15251, 2006). Even though this is based on comfort (perceived air quality – odour and irritation) and health, the health criteria is assumed to be met by the required ventilation for comfort. However, studies show that increased ventilation rates will have increased health and performance benefits. Wargocki *et al.* (2000) showed that overall productivity in a normal office increased on average by 1.7% when ventilation was increased from 3 to 30 L/s per person and Bako-Biro *et al.*

(2007) also showed that pupils' work rate increased by about 7% when ventilation rate was increased up to 16 L/s per person. A review on ventilation rates and health suggests that ventilation rates of up to 25 L/s per person are associated with reduced sick building syndrome (SBS) symptoms (Sundell *et al.*, 2011). Other issues associated with poor ventilation rates include high CO_2 levels, volatile organic compounds (VOCs) and other chemical pollutants. Increased levels of CO_2 above 1000 parts per million (ppm) are associated with physiological symptoms such as sleepiness, headache and drowsiness (Seppanen *et al.*, 1999). These symptoms tend to dissipate when CO_2 levels are reduced. Seppanen found that as indoor CO2increased from 1000ppm, SBS symptoms increased in office buildings. Studies carried out in a number of primary schools concluded that increased levels of CO_2in the classroom resulted in decreased levels of student attentiveness and concentration by approximately 5% (Coley and Greeves, 2004). They indicated that CO2levels can rise to about 4000ppm in classrooms during occupancy (acceptable for schools < 1500ppm (DfE, 2006). This magnitude of the reduction in attentiveness is likened to when school children skip breakfast. A study carried out in 96 Danish homes indicated that increase in the concentration of house dust mites, due to high relative humidity (RH), increased the risk of sensitization and exacerbated allergic symptoms in occupants (Having *et al.*, 1993). High RH could be the result of low ventilation rate in the space. With airborne infectious diseases, the risk of spread of infection is related to ventilation rates. A review by Li *et al.* (2007) on the role of ventilation in airborne transmission concluded that there is strong and sufficient evidence of a link between ventilation and the spread of infectious diseases such as measles, tuberculosis, small pox, influenza and Severe Acute Respiratory Syndrome.

Window-opening behaviour

In buildings, occupant behaviour will have an impact on energy use and the indoor environmental conditions. The adaptive approach to comfort is now a well-established concept and it indicates that if a change occurs such as to produce discomfort, people will react in ways which tend to restore their comfort (Humphreys and Nicol, 1998). Window use is one of the key adaptive strategies and most studies in this field have focused on the link between window use and temperature. Several studies have monitored window use and measured environmental parameters to understand the relationship between these. These experiments were conducted in naturally ventilated buildings, for differing time periods and in different seasons. Some studies found that indoor temperature is closely related to window opening behaviour (Rijal *et al.,* 2007 and Haldi and Robinson, 2009). In the latter study, time of day was also considered to contribute to window use. They suggested that occupants in an office use windows mostly on arrival and this could be due to a perceived difference in thermal and/or olfactory stimuli compared to their previous environment. Some other studies also showed that outdoor temperature has a strong link to window opening (Warren and Parkins, 1984, Fritsch *et al*., 1990, Rijal *et al*., 2007 and Dutton and Shao, 2010). Dutton and Shao noted that window use behaviour differs significantly in different seasons and one variable is not sufficient to predict the behaviour. All of these field studies have been conducted to better understand occupant behaviour motivations. Some pollutants are undetectable by occupants but others such as CO_2 have physiological effects. Whether the occupant will respond to this effect to control their own environment however is currently unknown. This is key to understanding whether occupant controlled ventilation can regulate CO_2 levels in well-sealed buildings. The question therefore is do occupants open windows to control thermal comfort alone or also to regulate CO_2 levels? This has important connotations for design if the assumption is the occupant will control their own ventilation, and in scheduling window use in building simulation as occupant window behaviour will have a significant impact on building energy use.

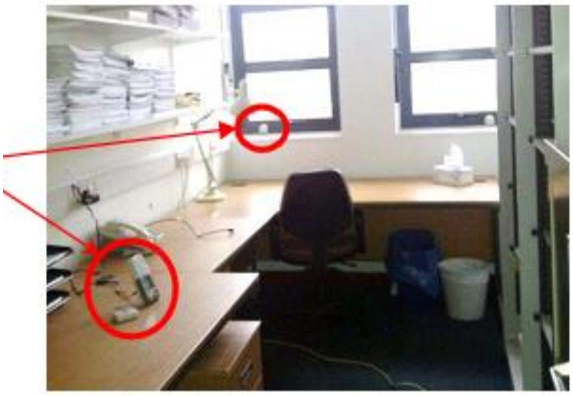
Summary and aims of the study

In naturally ventilated buildings, windows play a key role in adaptive thermal comfort as well as the energy performance through purpose-driven ventilation heat loss. Mechanical ventilation systems are often designed with the expectation of providing comfortable environmental conditions. However, these systems expend energy and they require the building to be virtually airtight to function efficiently. Buildings with air conditioning have been found to consume up to four times the energy of those with natural ventilation (Roaf, 2004). New and innovative building designs and construction techniques are being developed with the main driver being to reduce energy demand through increased insulation and improved airtightness to reduced heat loss. In light of this, the aim of this project is to observe if occupants will adapt their environment using manually-operated windows to adapt their thermal comfort and maintain ideal concentrations of CO_2. A controlled experiment is being conducted to develop an understanding of occupant window use behaviour in response to indoor temperature and CO_2 concentration. Initial results from the pilot study are presented.

2. EXPERIMENTAL STUDY

Study methodology

The study focuses on the relative importance of temperature and CO2on occupant control of ventilation in a single person office. Participants are required to work normally on individual occasions in an office where indoor environmental conditions and window intervention are monitored. An office in a University building in Sheffield, UK, was selected for the experiment (Fig. 1). The office is set at one of four different initial conditions – comfort temperature (20°C) and background CO_2 (approximately 350ppm), comfort temperature and high CO_2 (3000ppm), high temperature (28°C) and background CO_2 and high temperature and high CO_2. The comfort temperature was selected because it represents good thermal comfort in offices and the high temperature is the benchmark value for overheating in buildings (CIBSE, 2006). The occurrence of this high temperature should not exceed 1% of annual working hours (25 – 30 hours). The high CO2level was selected because it is greater than the level at which occupants begin to experience physiological effects but also below the recommended long term work place exposure limit set by the Health and Safety Executive (HSE, 2005). A portable convector heater is used to increase the room air temperature and dry ice is used to increase the indoor CO_2 concentration. A fan is used to ensure circulation and uniform distribution of the CO_2 gas which is fully sublimated prior to the participant’s arrival. For this study a sample size of forty-one were observed. Participants are asked to work in the room for approximately 30 minutes. A short duration was selected because it has been shown that occupants use windows to adapt their environments on entry to a room (Warren and Parkins, 1984 and Haldi and Robinson, 2009). All windows are closed before the participants arrive at the start of a test session and they are told to adapt the room to their person preference. This includes using the windows, adjusting light levels and seating.



Monitoring kit to record data on indoor environmental conditions and

Figure 1. Typical office with monitoring equipment

Monitoring methods

Indoor air temperature and CO_2 concentration were continuously monitored using Hobo Data Loggers (Tempcon, UK). Window intervention was monitored using state data loggers attached to the window and the frame. This records window state in binary form (0 – opened, 1 – closed). Simultaneous to the physical measurements, measures of self-assessed environmental perception and comfort were recorded by each participant during the experiment. The participants were issued with questionnaires at the start and end of the experiment which asked about their perception of the indoor environment and any adaptive strategies employed to change the indoor environment (including light levels, thermal comfort, acoustics, air quality and furniture arrangement).

3. RESULTS

The results presented here are the raw and analysed data from the physical observation (Table 1). Tests have been carried out for comfort and high internal temperature with low CO2and comfort internal temperature with high CO2. These were carried out during the heating season (November – December 2011). The data was analysed in categorical form – comfort/high temperature, high/low CO2and window opened/did not open. The Pearson’s chi-squared test was used to test the relationship between the categorical variables and to assess the measure of association. This is presented as χ2 demonstrating the difference between the observed and expected data and the statistical significance of the difference with p, where values are taken as significant when $p< 0.05$. The critical value for χ2 at one degree of freedom is given as 3.84 for $p< 0.05$. Above this value, the difference between the frequencies is statistically significant. In cases where the expected frequencies were less than 5 (for comfort temperature with high CO_2 – see Table 1), significance values were calculated using Fisher’s exact test.

Table 1: Results showing number of individual occupants for each test, and whether windows were opened or not opened at the different internal conditions

Initial internal condition			**Action on window**		**Total**
CO_2	**Temperature**		**Opened**	**Did not open**	
Low	Comfort	Observed frequency	2	10	12
		Expected frequency	5.2	6.8	12
		% Action on window	15.4	58.8	40
	High	Observed frequency	11	7	18
		Expected frequency	7.8	10.2	18
		% Action on window	84.6	41.2	60
High	Comfort	Observed frequency	2	9	11
		Expected frequency	4	7	11
		% Action on window	13.3	34.6	26.8

Comparing the scenarios with comfort/high internal temperature with low CO_2, the results indicate that the difference between the observed and the expected frequencies is statistically significant, with $\chi2(1)= 5.792$, $p< 0.05$. This implies that internal temperature has an effect on occupant action on windows. Comparing the effect of high and low CO_2, a difference was obtained between the observed and the expected frequencies. However this difference was not statistically significant, with a chi-square value, $\chi2(1) = 2.195$, $p> 0.05$. One reason for this is the small sample size used for high initial CO_2 condition, which means that some of the assumptions of a chi-square test were not met. Even though Fisher's exact test can be used to overcome this, CO_2 was not shown to be a contributing environmental factor that influences window use. This test will be repeated to increase the sample size and tests will also be carried out for high internal temperature with high CO_2.

4. DISCUSSION

Results from the controlled experiments illustrate the relative importance of thermal comfort and CO_2 on occupant window use. Some studies have suggested that occupant behaviour is a response to the immediate environment they are accommodating and suggest that indoor temperature is the most fundamental factor influencing occupant use of windows (e.g. Humphreys and Nicol, 1998, Yun and Steemers, 2008). The data collected from the monitoring exercise reflects the general trend that occupants will use openable windows to adjust their thermal comfort. In other words, indoor temperature is an essential contributing factor and at higher indoor temperatures, the probability of occupants opening the window increases.

CO_2 concentration is an important parameter of IAQ and it can be used as an indicator of adequate ventilation. Elevated amounts of CO_2 imply that there is insufficient fresh air entering the space and it can also be used as an approximate surrogate for concentrations of other occupant generated pollutants. More importantly CO_2 levels above 1000ppm results in complaints of stale and stuffy air, poor concentration and loss of attention. Preliminary results from this experiment showed that at comfort temperature and high CO_2 concentration (3000ppm), CO_2 did not influence occupant use of windows to control ventilation. From the questionnaires, 72% of participants reported that the air was stuffy and the room was not properly ventilated. However, only 18% of participants opened the window to adjust this. This suggests that other factors may have influenced occupant use (or lack of) of windows to control ventilation. The office building used is located next to a relatively busy road. The average background noise measured when the windows were closed was 56dBA and when the windows were opened it was 57dBA (acceptable noise level for an office is 35dBA (CIBSE, 2006). 55% of the participants stated that this increased noise level was distracting and not acceptable and this may have prevented them from opening the window. This may suggest that higher importance is given to the role of external noise in controlling natural ventilation. Another factor that could have affected the results of this study is the external thermal conditions, as previous studies have found a relationship between window use and the external temperature. During the winter months, outdoor temperature is considerably lower and therefore avoiding cold draughts could bean influencing factor affecting occupant window opening behaviour.

5. CONCLUSIONS

The results of the effect of three initial conditions (comfort temperature and background CO_2, comfort temperature and high CO_2 and high temperature and background CO_2) have been investigated and presented here. The results presented here show the relative impact of thermal comfort and high CO_2 concentrations on occupants use of windows. Although based on a small sample size, the results reflect the general trend observed by others in terms of the important role indoor temperature play in window use to control ventilation. The effect of increased CO_2 does not seem to influence occupant use of windows during the winter season. Further work will be conducted to assess the effect of high temperature and high CO2at varying outdoor temperatures. Work to develop the experimental methodology is ongoing. This will extend the experiment over the unheated seasons and adapt the questionnaires to obtain more detailed information about occupant control.

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