ANALYSIS OF FACTORS INFLUENCING THE MODELLING OF OCCUPANT WINDOW OPENING BEHAVIOUR IN AN OFFICE BUILDING IN BEIJING, CHINA

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ABSTRACT

This paper introduces a longitudinal study monitoring occupants' window opening behaviour in a mixed-mode office building in Beijing, China, when natural ventilation is specifically used for controlling the building's indoor thermal environment. Based on the field measured data, the influence of factors, including outdoor air temperature, outdoor PM2.5, indoor air temperature, time of day, occupancy and previous window state, on the observed state of windows is analysed. All of them are influential on occupants' window opening behaviour in the case study building, and so they can be used to model occupants' window opening behaviour in buildings in China to achieve a better consideration of occupant behaviour in dynamic building performance simulation.

KEYWORDS

Office building, Window opening behaviour, China, Behaviour modelling, Building performance simulation

INTRODUCTION

Buildings are huge energy consumers in the current society (EC, 2013). In order to reduce their energy consumption, natural ventilation and mixed-mode ventilation have been adopted widely for cooling buildings in summer (CIBSE, 2004). This is mainly achieved by increasing the air change rate between indoors and outdoors, usually through opening windows (Wallace et al., 2002). In a great number of buildings adopting natural ventilation and mixed-mode ventilation, windows are controlled manually by the building occupants. Therefore, people play an important role in the thermal performance of those buildings (Fabi et al., 2012). In the past 30 years, a number of studies with respect to occupants' window operation in office buildings have been carried out in European countries, such as the UK (Wei et al., 2013, Yun et al., 2008, Zhang and Barrett, 2012, Rijal et al., 2007), Denmark (Andersen et al., 2013), Germany (Herkel et al., 2008), the Netherlands (Guerra-Santin and Itard, 2010) and Switzerland (Fritsch et al., 1990, Haldi and Robinson, 2009), to better understand how, when and why occupants change the state of their windows and then develop reliable window opening behaviour models for dynamic building performance simulation. Generally, studies in this research area follow a general process, as shown in Figure 1. In this process, an accurate monitoring of window usage (state of windows at different time) and potential influential parameters, followed by a critical determination of influential factors are fundamental for developing reliable window opening behaviour models.

From existing studies carried out in Europe, several factors have been suggested to be influential on occupants' window opening behaviour in buildings, as listed in Table 1. Based on how the building occupants are classified when modelling their window opening behaviour, the factors that influence window opening behaviour can be grouped into three tiers. Tier 1 defines those factors that are common to all occupants within a building, including all environmental factors, season, time of day, previous window state and presence; Tier 2 includes factors that can further classify the building occupants into several sub-groups, and they are window type, window orientation, floor level, shared offices/rooms, building type, room type, heating system type, occupant age, occupant gender, property ownership and smoking. Generally, Tier 2 factors are related to the property of either the building itself or the occupants within the building; Tier 3 only has personal preference, whose influence is beyond the factors within Tier 1 and Tier 2. This factor is used to present the condition that even when all other factors defined in Tier 1 and Tier 2 are the same, in actual buildings occupants may still perform differently regarding to their use of office windows. Although most existing studies of modelling occupant window opening behaviour were based on Tier 1 factors, an involvement of Tier 2 and Tier 3 factors in the modelling will be helpful on increasing the modelling accuracy (Wei et al., 2014).

In order to build standardised framework of defining, modelling and simulating occupant behaviour, including window opening behaviour in buildings, the IEA (International Energy Agency) has launched a new international collaborative project, ANNEX 66: Definition and Simulation of Occupant Behaviour in Buildings, at the end of 2013 (IEA, 2013). Currently, there are researchers from more than 24 countries contributing to this 4-year project. To complete this project, a huge number of behavioural studies from various locations around the world are needed. Currently, however, high quality data regarding people's use of windows from buildings in China are still lacking. Therefore, this study introduces some results from a longitudinal study monitoring occupants' window opening behaviour in a mixed-mode office building located in Beijing, China. Using the field collected data, the influence of factors listed in Table 1 is evaluated in this work.

RESEARCH METHODS

The study was carried out in a mixed-mode office building, as shown in Figure 2 (left), which is located on the main campus of the Beijing University of Technology (BJUT) (39° 54' 27'' N, 116° 23' 17'' E, alt. 44m) in Beijing, China. The building has two floors. The ground floor has three laboratories and the first floor has seven offices with nominally the same floor area (10 m^2) and layout (Figure 2 right). Each office can have two occupants working simultaneously but during the survey period all monitored offices were occupied by only one specific occupant. In each office, there are two gliding windows that are facing south. The building is heated in the winter time using a central heating system, and it is cooled in the summer time by split air-conditioners. During the transitional periods of the year (from the middle of March to the end of April and from the beginning of October to middle of November), natural ventilation is adopted as the primary cooling strategy.

The field monitoring was carried out in two transitional seasons in year 2014, i.e. from 16th March to 30th April, and, from 8th October to 15th November, during which the building was cooled specifically using natural ventilation. During the survey, five offices on the first floor (account for 70% offices in the building) were monitored for room occupancy (1 minute interval), window state (1 minute interval) and indoor air temperature (5 minute interval; accuracy: ±0.35°C), as shown in Figure 3a to 3c. Concurrently, outdoor air temperature was measured and recorded every 5 minutes by a weather station (accuracy: ±0.5°C) installed locally on the roof of the case study building, as shown in Figure 3d. The PM2.5 (in the unit of μg/m^3) was measured at a nearby public weather station and the values can be downloaded from its official website (AQISTUDY, 2015).

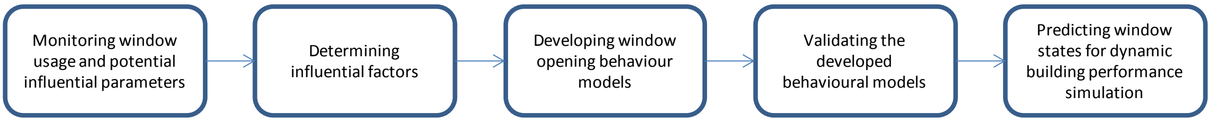
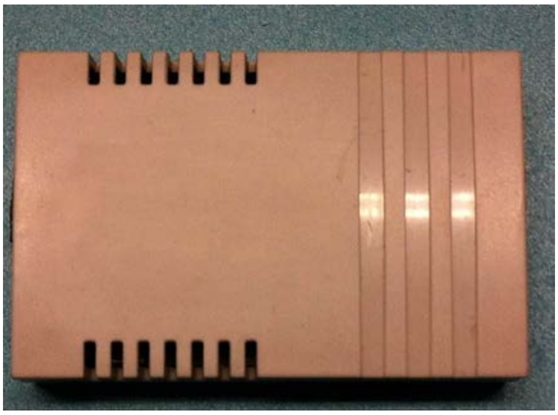


Figure 1. General process of a window opening behaviour study

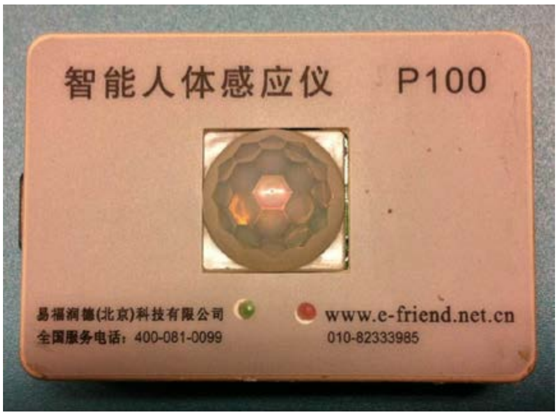
Figure 2. The case study building (left) and a typical office (right)

Table 1. Influencing factors of occupants' window opening action (Wei, 2014)

TIER	FACTORS
1	Outdoor climate (dominated by outdoor air temperature); Indoor climate(dominated by indoor air temperature); Season; Time of day; Previous window state and Presence
2	Window type; Window orientation; Floor level; Shared offices/rooms; Building type; Room type; Heating system type; Occupant age; Occupant gender; Property ownership and Smoking
3	Personal preference



(a) Indoor air temperature



(b) Occupancy

(c) Window state

(d) Outdoor air temperature

Figure 3. Monitoring devices

This study has a limited number of samples regarding to the monitored offices. This is acceptable when all important parameters are measured by electronic devices, due to the cost intensive nature of this monitoring method (Weihl and Gladhart, 1990): Yun and Steemers (2008, 2010) carried out their study in six and three offices, respectively; Li et al. (2015) conducted their monitoring in five offices; Dutton and Shao (2010) monitored window use in two classrooms. To better handle this limitation, this study only analysed the influence of Tier 1 factors as they are common to all building occupants so not much restricted by the sample size. Additionally, as in the past two years air pollution caused by PM2.5 was a major issue in Beijing, its impact on occupant window opening behavior is examined in this study as well.

RESULTS

Using the field data collected from the case study building, the influence of outdoor air temperature, indoor air temperature, time of day, presence and previous window state was analysed and the results are presented sequentially in the following part of the paper.

Outdoor air temperature

The influence of outdoor air temperature on the state of the office windows was evaluated by plotting the percentage of opened windows against the outdoor air temperature (Tout). During the measurement, the outdoor air temperature was varying between 3.5°C to 38.8°C, a big range. Therefore, the percentage of opened windows was calculated for every binned Tout at 3°C intervals, not 2°C as used in existing studies (Wei et al, 2013, Nicol and Humphreys, 2004). In order to eliminate the effect from presence and time of day, only the samples collected at the intermediate period (when the occupants have settled down in the office and also not trying to leave the offices) were used in the analysis. The result is shown in Figure 4, in which the error bars for each percentage value was calculated by the Adjusted Wald Method (Sauro and Lewis, 2005). They reflect the accuracy of an estimated percentage with respect to the sample size of the measurement (the higher the number of samples, the narrower the error bar, hence the closer to real values). Figure 4 shows that the percentage of opened windows during the intermediate period is generally proportional to the outdoor air temperature. This finding is consistent with that previously observed in European countries (Zhang and Barrett, 2012, Wei et al., 2013, Haldi and Robinson, 2009, Herkel et al., 2008, Rijal et al., 2007).

Outdoor PM2.5

PM2.5 refers to the atmospheric fine particulate matter, which has a diameter less than 2.5μm. It can penetrate deeply into human's lung and cause serious health problems (Zhao et al., 2015). In the past two years, Beijing has suffered greatly by PM2.5 as outdoor air pollution, especially in the winter and transitional seasons. Therefore, the impact of PM2.5 on occupant window opening behavior was analyzed using the field measured data in the study. Due to the high dependency of window states on outdoor air temperature (Wei et al., 2013, Zhang and Barrett, 2012, Haldi and Robinson, 2009, Herkel et al., 2008, Rijal et al., 2007), window states cannot be correlated to PM2.5 without outdoor air temperature. Therefore, the analysis here is a 3-D problem rather than a 2-D problem so the visualization method used in Figure 4 cannot be used. Instead, logistic regression analysis was used in the study to identify whether outdoor PM2.5 has a significant impact on the state of windows in the investigated building. Logistic regression analysis (Hosmer and Lemesbow, 2000) is a statistic method that defines the probability of specific event happening, such as opening a window, according to various influencing factors, such as air temperature. When using logistic regression, a useful method to identify the contribution of individual factors to the event happening is the Wald statistic test. The Wald statistic has a chi-square distribution, so a significant two tailed P-value of a particular predictor reflects that this predictor plays an important role in the logistic regression model. In this analysis, both outdoor air temperature and PM2.5 were used as predictors and the observed state of windows was used as the model output. The regression results gave that both predictors have a P-value of 0.000, meaning that both predictors have significant influence on the observed window states.

Indoor air temperature

The same samples and method as used above were used for analysing the influence of indoor air temperature. During the survey, the measured indoor air temperature was ranged between 13.7°C and 34.9°C. In the analysis, the indoor air temperature was binned every 2°C, as used in existing studies (Wei et al, 2013, Nicol and Humphreys, 2004). Figure 5 plots the relationship between the percentage of opening windows and indoor air temperature, from which a general proportional relationship is observed, complying with previous studies carried out in Europe (Yun et al., 2008, Rijal et al., 2007).

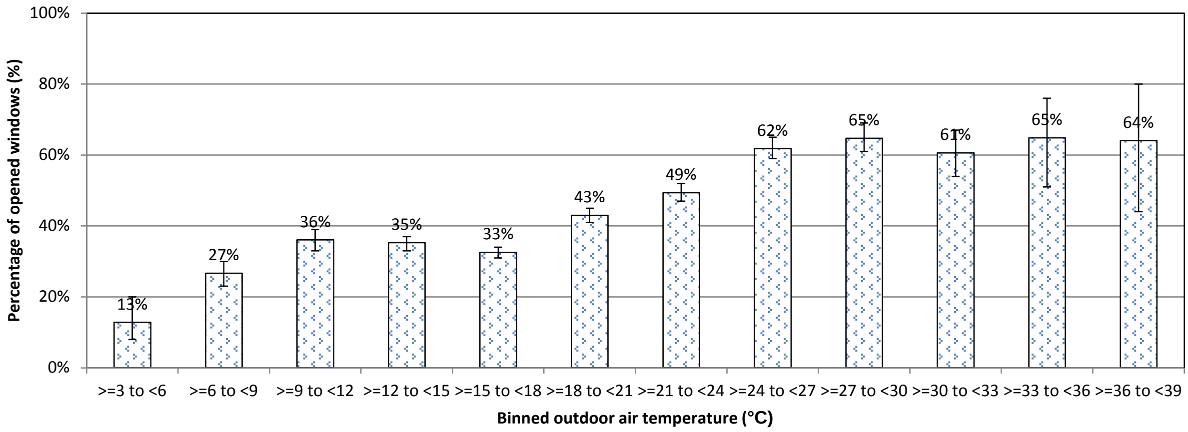


Figure 4. Percentage of opened windows as a function of outdoor air temperature

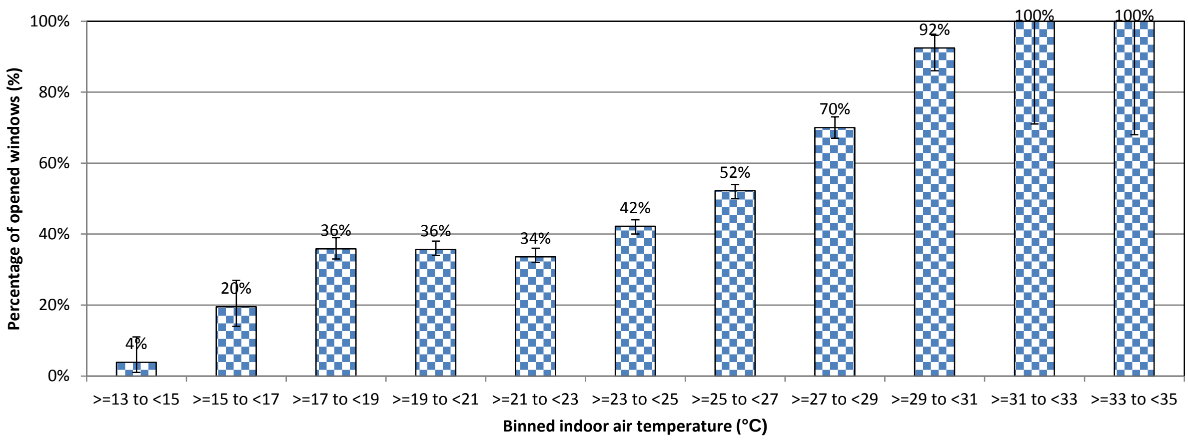


Figure 5. Percentage of opened windows as a function of indoor air temperate

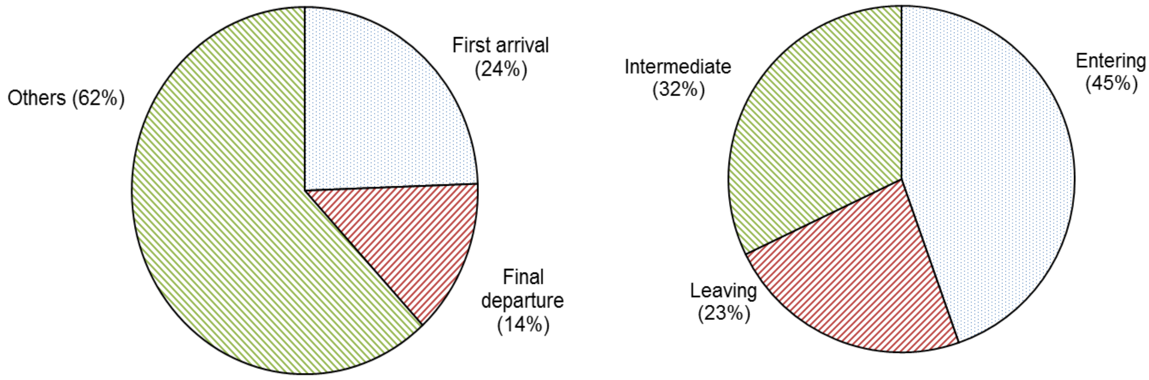


Figure 6. Percentage of 'window state changes' according to time of day (left) and presence (right)

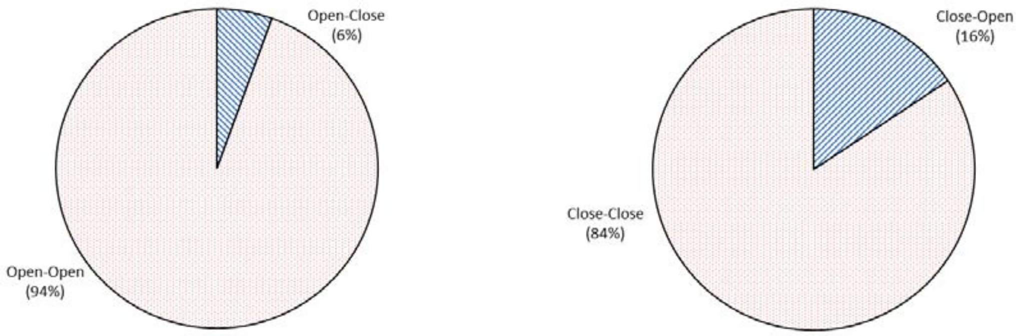


Figure 7. Percentage of window operations at first arrival time for opened windows (left) and closed windows (right)

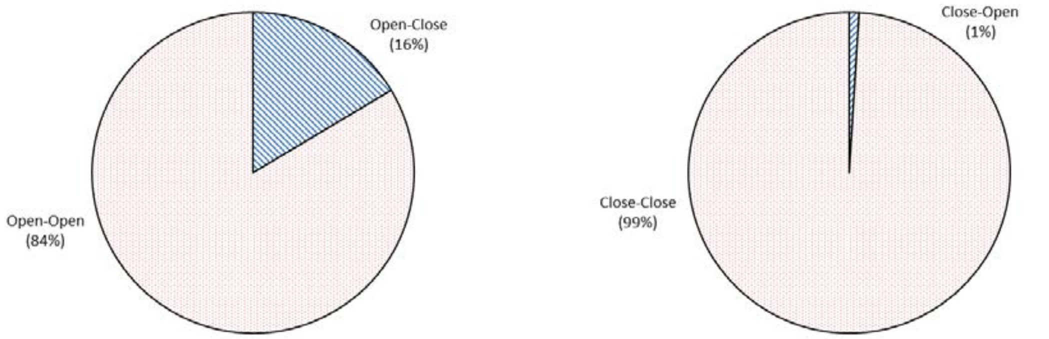


Figure 8. Percentage of window operations at final departure time for opened windows (left) and closed windows (right)

Time of day and presence

Exiting studies in this area have suggested that occupants tend to open windows more when they first arrive at the offices and prefer to close windows when they finally leave the office (Haldi and Robinson, 2009, Herkel et al., 2008, Yun et al., 2008). This is reflected by a factor called 'time of day'. Using the data collected in this study, the influence of this factor was evaluated for Chinese people and the result is shown in Figure 6 (left). The pie chart reflects that 38% (24%+14%) of changes of window states occurred when the occupants firstly arrived at or finally left their offices on working days. Those 'others' in the comparison include conditions such as intermediate time and temporary departures during working hours.

As presence has been suggested in previous studies (Haldi and Robinson, 2009) to be another factor causing changes of window states, its influence is evaluated in Figure 6 (right), combining intermediate arrival and intermediate departure during working hours with first arrival and final departure. It could be found that 68% (45%+23%) of window operation happened when entering or leaving the offices.

Previous window state

The influence of previous window state on the current window state was analyzed for different times of the day, i.e. first arrival, intermediate and final departure. Figure 7 (left) depicts the percentage of occupants' window operations at first arrival at their offices when the office window was left open during the last night. It demonstrates that if the window was left open in the last working day, then more than 90% cases the occupants would keep them open. Figure 7 (right) shows the result when the window was closed before occupants arrive at the offices and it reflects that occupants prefer to keep it closed at this condition. This means that at the first arrival time, occupants pretend to keep the window state unchanged, so the previous window state has a significant impact on occupants' window operation at the time of first arrival in Chinese buildings, as found in previous studies (Haldi and Robinson, 2009).

Figure 8 plots the results for the final departure time. The same as for the first arrival time, occupants intend to keep the window open when it has been opened during the working hours and keep it closed when it has been closed. Additionally, comparing Figure 7 and Figure 8, it could be found that occupants prefer to close more windows when finally leaving the office, comparing to when firstly arriving at the office, and prefer to open more windows when firstly arriving at the office, comparing to finally leaving the office, as found in European studies (Haldi and Robinson, 2009, Herkel et al., 2008, Yun et al., 2008).

For the intermediate period, Rijal et al. (2007) has suggested that if the window has been opened, people will not close it until they feel cold again, and vice versa. To reflect this influence, they have used a 'deadband' of temperatures in which window opening remains constant. This hypothesis has been tested in this study for Chinese people and a 1.3°C deadband was observed (for intermediate period, the mean indoor air temperature for changing window state from open to closed is 22.1°C while the mean indoor air temperature for changing window state from closed to open is 23.4°C).

DISCUSSIONS

Occupant behaviour in buildings is a complex process (Wei et al., 2014, Fabi et al., 2012) and it is one of the most important uncertainties in dynamic building performance simulation (De Wilde 2014). Occupant window opening behaviour can directly influence the performance of buildings, especially under natural ventilation/mixed mode conditions. In order to solve this issue, studies have been carried out in Europe and some useful window opening behaviour models have been developed for dynamic building performance simulation. As described in Figure 1, these studies generally followed a general investigation process and an accurate capture of occupants' window usage and then determine influential factors are fundamental for developing a window opening behaviour model that can be used for simulation. This paper has introduced results from a longitudinal study on occupant window opening behaviour. The study was carried out in China where high resolution data in this research area are still lacking. The results covered in this paper come from the first two steps shown in Figure 1, with a high resolution longitudinal monitoring of occupants' window usage and potential influential factors in an office building and critical identification of factors that influence the window usage. In the next step of the study, these influential factors will be used to model the monitored state of windows using logistic regression analysis (Hosmer and Lemesbow, 2000), which has been commonly used in European studies for modelling window opening behaviour. Figure 9 has depicted a logistic model developed based on the monitored data from this study (named as the 'BJUT model'), and it defines the correlation between the percentage of opened windows and outdoor air temperature during the intermediate period of working days. Meanwhile, the BJUT model has been compared with two published models developed in European studies (Rijal et al., 2007, Haldi and Robinson 2009).

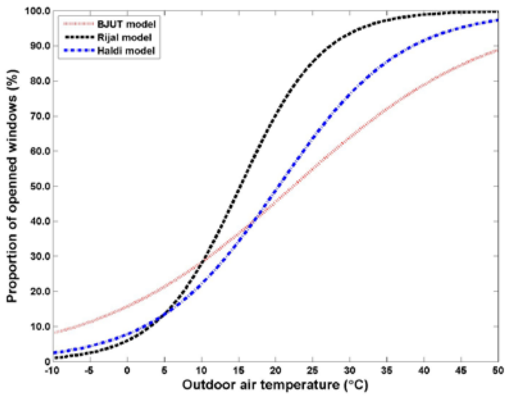


Figure 9. Proportion of windows open as a function of outdoor air temperature; comparison of the data gathered in this study and the work from Europe

Figure 9 reflects that people in China act similarly to those in Europe, when outdoor air temperature changes: open more windows at higher outdoor air temperatures. However, it seems to be that the curve for people in China is not as steep as those for people in Europe, and this means people in China do not response to the change of outdoor air temperature as actively as those in Europe, at least for the samples investigated in the studies included in Figure 9. This difference will be further investigated in future studies. Additionally, due to the high air pollution in Beijing in the past years, PM2.5 has been found to be influential on occupants' decision of opening windows and this factor has not yet been analysed in European countries. All these two aspects (different responses and missing factors) will possibly affect the usability of behavioural models' developed in Europe for simulation applications in China.

CONCLUSION AND IMPLICATIONS

Occupants' window opening behaviour has a significant impact on the thermal performance of naturally ventilated and mixed-mode buildings. In the past 30 years, several studies have been undertaken in European countries in order to explore the drivers for occupants to open office windows, so occupant window opening behaviour can be better modelled in dynamic building performance simulation. In this research area, studies that are carried out in Chinese buildings are still highly required.

This paper introduces a longitudinal study monitoring occupants' window operation in a mixed-mode building in Beijing, China. Using the data, the influence of important drivers of opening windows, also found in previous studies, were evaluated for Chinese occupants. This includes outdoor air temperature, indoor air temperature, time of day, presence and previous window state. Additionally, due to the serious air pollution from PM2.5 in the past two years in Beijing, the influence of outdoor PM2.5 was analysed as well. The analysis reveals that all of the factors examined in this study can influence the state of windows in a Chinese office building, meaning that Chinese occupants have similar action as European people with respect to opening and closing windows, hence similar modelling methods should be usable for modelling occupants' window opening behaviour in office buildings in China for dynamic building performance simulation. This study, however, has a limited number of participants so a broader study containing a wider range of people and buildings is still required to test the influence of other factors. Although the results introduced in this paper is based on early-stage analysis of a field study investigating occupant window opening behaviour, it provides valuable and critical information that can be used for later model development and building performance simulation.

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