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A Probabilistic Prediction Model for Window Opening during Transition Seasons in Office Building

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Abstract. Window operation of occupants in building has close relationship with indoor air quality, indoor thermal environment and building energy performance. The objective of this study was to understand occupants' interaction with window opening in transition seasons considering the influence of subject type (e.g. active and passive respondents) and to develop corresponding predictive models. An investigation was carried out in non-air-conditioned building in the UK covering the period from September to November. Outdoor temperature in this study was determined as good predictor for window operation. The differences in window opening probabilities between active and passive subjects were significant. Active occupants preferred to open window for fresh air or for indoor thermal condition adjustment, even though the outdoor air temperature sometimes were less than 12 ℃. Proper utilization of windows in transition seasons contributed significantly to building energy saving and further improve energy efficiency in buildings.

1. Introduction

Occupants' adaptive behaviours help with either adjusting surrounding thermal conditions to meet people's thermal preferences or adapting to ambient thermal environment. Comfortable indoor thermal environment is of great benefit to study performance, working efficiency, wellbeing of human body and building energy performance. Windows as effective environmental control for ventilation and cooling play a significant role of improving indoor thermal condition and reducing building energy consumption. Therefore, the interaction of occupants with window attract more and more attentions.

Dick and Thomas [1], Brundrett [2] and Lyberg [3] were the pioneers who studied the window operation in residential buildings. They found that window opening was significantly influenced by outdoor air temperature. In recent decade, the researches in this field focus on not only the use frequency of window but also the development of stochastic models for predicting window opening or closing probability or transition probability under certain thermal condition. For example, Window using frequencies in different seasons considering the effect of orientation was presented by Liu et al [4]. based on data collecting from a whole year's on-site measurement in non-air-conditioned office building. Sun et al [5]. investigated the relationship between thermal feelings of subjects and window operation by performing an investigation on adaptive behaviour of occupants in ten mixed-mode buildings during summer time in Northern China. Jones et al [6]. developed stochastic model using multivariate logistic regression to predict main bedroom window operation on the basis of data gathering from a year-long field study. Based on almost seven-year's measurements, Haldi et al [7]. predicted transition probabilities for window changing from open to closed or from closed to open by employing Markov process. But, these studies seldom considered the case of window operation in transition seasons. In fact, window operation impacted building energy consumption significantly during air-conditioners' off-running period in transition seasons [8]. Therefore, a filed study was conducted in non-air-conditioned office building in the UK during transition seasons (September to November) aiming to better understand the interaction of occupants with windows and further to provide more accuracy algorithm for building energy simulation.

2. Methodology

2.1. Environmental Parameters Measurement

The indoor environmental parameters including indoor air temperature (T_{in}), relative humidity (RH_{in}), globe temperature (T_g), air velocity (V_{ain}) were measure by a three-channel thermistor (TH-03 from Pico Technology), HumidiProbe from Pico Technology and Testo 405-v1 anemometer, respectively. Meanwhile, successive 24-hour indoor thermal environmental monitoring in terms of indoor air temperature and relative humidity was also applied by using TinyTag (TGU-4500). All instruments, measurement duration and position met the corresponding requirements specified in ASHRAE 55 standard [9]. The outdoor climatic data comprising outdoor air temperature (T_{out}), outdoor relative humidity (RH_{out}), outdoor wind speed at 2m (V_{out2m}) and outdoor wind speed at 10m (V_{out10m}) during the survey period were provided by the University of Reading atmospheric observatory.

2.2. Questionnaire Survey

Questionnaire survey here was intended to collect information on thermal perceptions, environmental control availability, environmental control perceived level, use frequencies of environmental controls, the purpose of environmental control utilization and supplement strategies, etc. The questionnaire survey was performed simultaneously with environment variables measurement, 2-3 days per weeks covering transition seasons. In addition, the instant adaptive actions performed by subjects and corresponding thermal sensation were filled in thermal diary on each working day covering the period from arrival to departure.

2.3. Driving Stimulus

The influence of Indoor air temperature [7][10], CO_2 concentration [11], $PM_{2.5}$ concentration [12], outdoor air temperature [7][10], season [10], time of the day [10], occupancy pattern [7][10] and personal preference [12] etc. had been investigated in recent ten years' studies. The interaction between occupants and surrounding thermal environment via performing adaptive behaviour is a complex process. Thus, there is no agreement on the environmental driving force for a window opening event reached. In this study, the impact of indoor air temperature, indoor relative humidity, globe temperature, air velocity, outdoor air temperature, outdoor relative humidity, outdoor wind speed at 2m and outdoor wind speed at 10m are identified by applying multi-factor variance analysis. The results show that only the outdoor air temperature's Sig. value is less than 0.05. The Sig. values of other physical environmental factors are all exceed 0.05. Therefore, outdoor air temperature is regarded as the physical impact factor influencing occupants' adaptive action on windows. In addition, according to the answers to question of 'if you could adjust the window, how often would you do so?', all occupants were divided into two sub-categories, active and passive subjects, respectively. Thus, the influence of subject type on window operation was considered in this study.

3. Results

3.1. Building Description

The surveyed building is located in Whiteknight campus, University of Reading, UK. It is designed as non-air-conditioned with heating supplied in winter. Figure 1 shows the north façade of the building. This building has four floors with north-south orientation and flat roof. The structure is brick-concrete. The windows are single-glazed with aluminium alloy frames. It was usually occupied by lecturers, administrative staff, academic researchers and students.

Figure 1. The surveyed building.

3.2. Indoor and Outdoor Thermal Conditions

Table 1 shows the indoor and outdoor thermal conditions in transition season covering from September to November. Except indoor air temperature and globe temperature, all physical environmental variables fluctuated significantly due to successive 24-hour monitoring. It was noticeable that the maximum value of indoor air temperature exceeds 30 ℃. This was because the subjects were observed putting the fan heaters which were in use around Tingtag. Such observation, to some extent, could also be used to explain the obviously differences between indoor and outdoor air temperatures. The indoor relative humidity level was less than that in outdoor. This could be attributed to the higher indoor air temperature as a result of the use of fan heaters. The higher indoor temperature enhanced the evaporation of water and thus led to lower indoor relative humidity. The significantly discrepancies were also observed between indoor air velocity and outdoor air velocity. The mean indoor air velocity value indoor was 0.03m/s comparing with 1.72m/s and 2.32m/s of outdoor air velocity at the height of 2m and 10m.

Table 1. Indoor and outdoor thermal environment.

	Indoor				Outdoor			
	T_{in} (℃)	RH_{in} (%)	T_g (℃)	V_{ain} (m/s)	T_{out} (℃)	RH_{out} (%)	V_{out2m} (m/s)	V_{out10m} (m/s)
Max	34.51	79.86	35.70	0.13	21.70	98.80	7.60	8.40
Min	13.70	18.50	18.50	0.01	-5.60	39.50	0.01	0.10
Mean	20.65	53.72	22.61	0.03	10.05	82.83	1.72	2.32
Std.	2.48	9.23	2.02	0.02	5.43	12.24	1.12	1.31

3.3. Window Opening Probabilistic Prediction Model

As mentioned above, outdoor air temperature in this investigation is as the physical factor influencing window operation. Meanwhile, the effect of subject type is also considered. Thus, in order to obtain a general understanding of window opening probability under a certain thermal environment, logistic regression is applied to binary data. Figure 2 demonstrates the predicted probabilities of a window state changing from closed to open for both occupant types. It clear that there are significant differences in window opening probabilities in transition seasons reflecting by the gap between the corresponding predicted curves. Such discrepancies are getting greater with the outdoor air temperature rising. It implies that active subjects are likely to open windows in their offices for fresh air or for cooling, particular in case that the outdoor air temperature exceeds 12 ℃. In contrary, no matter the air temperatures are in outside, passive occupants are reluctant to open the windows.

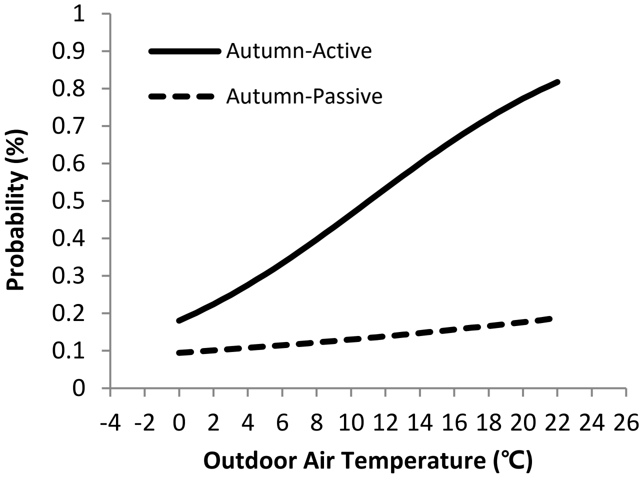

Figure 2. Prediction of widow opening probabilities.

The mathematical expression of figure 2, which considers the influence of subject type, are expressed as below:

For active subjects: $$P = \frac{e^{-1.514+0.137t_{out}}}{1+e^{-1.514+0.137t_{out}}} \quad (1)$$

For passive subjects: $$P = \frac{e^{-2.260+0.036t_{out}}}{1+e^{-2.260+0.036t_{out}}} \quad (2)$$

Nagelkerke R^2, P-values for both $G(\chi^2)$ and Wald statistics and standard error are calculated to reflecting the independent variables on dependent variables and to assess the overall fitting. The corresponding are presented in table 2. With respect to active respondents, the P-values of both overall test and independent variables test indicate that outdoor air temperature is a good predictor of window opening. The greater value of Nagelkerke R^2 also confirms the close relationship between outdoor air temperature and window operation. Over 12 ℃, the window opening probability will exceeds 50% and rising constantly in response to the increasing in outdoor air temperature. But in terms of passive subjects, since they are very reluctant to open windows to adjust indoor thermal conditions or for fresh air no matter how the temperature changes, their adaptive actions on windows occasionally occurs. As a consequence, the overall fitting is not ideal based on insufficient datasets.

Table 2. Summaries of regression results and statistical tests of window operation.

		Coefficient	S.E.	Wald	P-value of Independent Variables	Nagelkerke R^2	P-values of $G(\chi^2)$
Active	Tout	0.137	0.056	6.052	0.014	0.130	0.009
	Constant	-1.514	0.696	4.730	0.030		
Passive	Tout	0.036	0.062	0.345	0.557	0.007	0.552
	Constant	-2.260	0.753	9.001	0.003		

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3.4. Model Verification

The model verification is applied by comparing the probabilities of window opening on the basis of observed data and the probabilities of window opening predicted by the derived models, and then resort to correlation analysis, which demonstrates the degree of correlation between observed values and predicted values.

Table 3 illustrates the observed and predicted values of window opening at the interval of 1.0℃. The results of correlation analysis is presented in table 4. The Pearson correlation coefficient is 0.805 with P-value of less than 0.05 indicating high linear correlation between observed and predicted values. Thus, the derived model fit the observations well. The outdoor air temperature as predictor is also confirmed again.

Table 3. The observed and predicted values of window opening probability.

Outdoor air temperature (℃)	Window use frequency				Window opening probability			
	Passive		Active		Passive		Active	
	Open	Close	Open	Close	Observation	Prediction	Observation	Prediction
10	0	223	121	107	0.00	0.12	0.53	0.43
11	0	290	83	186	0.00	0.13	0.31	0.46
12	22	264	125	162	0.08	0.13	0.44	0.50
13	0	290	183	179	0.00	0.13	0.51	0.53
14	11	417	289	329	0.03	0.14	0.47	0.57
15	20	555	378	388	0.03	0.14	0.49	0.60
16	55	398	353	206	0.12	0.15	0.63	0.63
17	95	263	283	31	0.27	0.15	0.90	0.66
18	54	278	273	25	0.16	0.16	0.92	0.69
19	0	64	176	29	0.00	0.16	0.86	0.72
20	0	31	173	4	0.00	0.17	0.98	0.75
21	0	20	188	3	0.00	0.17	0.98	0.77
22	0	1	23	0	0.00	0.18	1.00	0.80

Table 4. The observed and predicted values of window opening probability.

		Observed probability	Predictive probability
Observed probability	Pearson correlation coefficient	1	0.805
	Significance (bilateral)		0.000
	N	24	24
Predictive probability	Pearson correlation coefficient	0.805	1
	Significance (bilateral)	0.000	
	N	24	24

4. Conclusions

A field investigation on window opening behavior of occupants in transition seasons was performed in non-air-condition building in UK. The conclusions are listed as follows:

- For fresh air is the main purpose of window opening in transition seasons, particularly for active subjects.
- In this study, outdoor air temperature is found to be better predictor for window operation comparing with the case that indoor air temperature is as independent variable.
- There are significant discrepancies in window opening probabilities between active and passive occupants. The occurrence probability of window opening will exceeds 50% in case that the outdoor air temperatures are over 12 ℃.

- Opening windows in a proper way in transition seasons play a significant role in reducing the reliance on energy-intensive HVAC systems in the process of creating thermal comfort indoor environment.

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