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Probabilistic modelling of human adaptive behaviour in non-air-conditioned buildings

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Abstract

In non-air-conditioned buildings, occupants are able to interact with their surrounding environment using various adaptive opportunities such as opening a window. The availability of these opportunities may make occupants feel thermally comfortable across a wider range of conditions than in air-conditioned buildings. Therefore, a good understanding of human adaptive behaviour is required to generate a realistic simulation of the thermal performance for non-air-conditioned buildings.

From a field survey carried out in four non-air-conditioned buildings in the summer of 2009, in Loughborough University, UK, it was found that occupants have different preferences when using adaptive opportunities to adjust their surrounding thermal environment. This paper presents a new approach that attempts to model human adaptive behaviour captured from occupant survey data. In addition, an adaptive preference model, which is a key part of the approach, is introduced in this paper.

Keywords

Building performance simulation, human behaviour modelling, adaptive opportunity, thermal comfort

Introduction

Building performance simulation is increasingly used in both academic and commercial applications. It is used to provide insights into building performance that can be used by architects and engineers, but also to other groups such as building occupants and facility managers, subcontractors and fabricators, and researchers in building development (Eastman 2008). In order to reduce the energy consumption of buildings without sacrificing thermal comfort levels inside, thermal comfort, which is defined by ASHRAE as *"that condition of mind which expresses satisfaction with the thermal environment"* (ASHRAE 2004), has gained great attention of researchers in the past several decades to evaluate the thermal comfort levels of indoor environments in the simulation of building performance. Based on experiments conducted in climate chambers, Fanger (Fanger 1970) developed a PMV model, which is a widely used approach for predicting people's thermal sensation. It is the basis of the method adopted in several building design standards, such as ASHRAE 55 (ASHRAE 2004), ISO 7730 (ISO 2005) and CIBSE Guide A (CIBSE 2006), to estimate thermal comfort levels in buildings. A number of studies conducted in different climate zones around the world have shown that in non-air-conditioned buildings, PMV does not provide a satisfactory prediction of thermal comfort (de Dear and Brager 2002). The occupants appear to feel comfortable in a wider range of conditions than suggested by Fanger's PMV model, and this is likely to be because they are active agents interacting with their surrounding thermal environment through various kinds of adaptations (behavioural adjustment, physiological acclimatization and psychological habituation or expectation) to secure their comfort sensation (Brager and de Dear 1998). In addition, the behavioural adjustment adaptation plays a significant role through available adaptive opportunities provided in buildings such as opening a window. Therefore, if the thermal performance of non-air-conditioned buildings is to be simulated more realistically, a good understanding of human adaptive behaviour becomes necessary.

Generally, occupants in non-air-conditioned buildings are able to adjust their surrounding thermal environment through performing the following adaptive actions: opening/closing windows, opening/closing doors, adjusting clothing insulation, adjusting air diffusers, adjusting solar shading devices, adjusting blinds/curtains, drinking cool/hot drinks, adjusting heaters and operating private fans.

Based on field surveys conducted in European and Asian countries (Rijal et al. 2007a; McCartney and Nicol 2002; Nicol et al. 1999), Nicol and Humphreys proposed specific models predicting the state of windows, fans and heating systems for naturally ventilated buildings (Nicol and Humphreys 2004) and mixed-mode buildings (Rijal et al. 2009) using logit functions. In their models, the indoor globe temperature is used for predicting the state of windows and fans, while the outdoor temperature is used as the predictor of the state of heating systems. Based on the work done by Nicol and Humphreys, Rijal et al. (2007b) made a refinement on their models by combining both indoor globe temperature and outdoor temperature for the prediction of window state in buildings.

In Germany, Herkel et al. (2008) carried out field studies monitoring the use of windows in 21 south-facing offices. He found that the user behaviour with regard to opening/closing windows had a strong correlation with season, outdoor temperature and occupancy of buildings. A quadratic equation was developed to represent the correlation between the probability of window opening/closing and outdoor temperature. In addition, 9 sets of coefficients were determined according to the time of day (arrival, intermediate and departure) and window positions (small open, large open and large tilted open).

Whilst important contributions, these methods cannot reflect the real human dynamic processes that lead building occupants to choose weather or not to execute adaptive actions (Haldi and Robinson 2008a). Another approach, which is based on discrete-time Markov process, had been adopted by many researchers to predict the window state.

Fritsch et al. (1990) had proposed a stochastic model to predict window opening angles using Markov chains for heating seasons based on field surveys conducted in four south-facing office rooms between October and May. It was found that the outdoor temperature had a meaningful effect on the human actions with regard to opening/closing windows.

In recent publications, Yun and Steemers (2009) proposed a series of models predicting the window state using Markov chains. These models were generated based on field surveys carried out in cellular offices in Cambridge, 2006. From their study, the probability of window state is defined as a function of the indoor temperature, as well as the time of day (arrival, subsequent occupation period), the occupants' perception of controllability (passive, medium and active window users), and the design of building facade.

To model human adaptive behaviour in buildings, Haldi and Robinson (2009a) had conducted several investigations over seven years in Lausanne, Switzerland. They used three mathematical approaches to predict the window state: logit distributions, discrete-time Markov process and survival distributions. From the logit distribution approach, the outdoor temperature was found to be the best predictor of window state. In the discrete-time Markov process approach, the state of window is affected by the time of day together with various indoor and outdoor stimuli (the opening actions are influenced mainly by indoor conditions, while the closing actions are affected by outdoor conditions). Although the discrete-time Markov process approach was widely used by researchers, Haldi and Robinson (2008a) pointed out that this process needed to choose a fixed time interval for the simulation, which will omit the prediction of short openings that are less than the chosen time interval. Therefore, they used a continuous-time random process, which is based on survival distributions, to predict the duration of window opening/closing, rather than the transitions between them. In this approach, the duration of window opening is a function of the outdoor temperature, while the duration of window closing is dependent on the indoor temperature.

Besides opening/closing windows, adjusting clothing insulation level is another significant way that occupants maintain their thermal comfort in non-air-conditioned buildings (Humphreys and Nicol 1998). Therefore, some field studies were carried out to determine how occupants select their clothes for daily work. In the 1980s, Fishman and Pimbert (1982) had found that in commercial buildings, the clothing insulation level had a strong linear correlation with the outdoor environment and season. Based on field studies carried out around the world, de Dear and Brager (1998) set up a relationship between clothing insulation levels and corresponding mean indoor operative temperatures for naturally ventilated and air-conditioned buildings. Through field studies conducted in 2 different places in Sydney, Australia, Morgan and de Dear (2003) concluded that the value of today's mean clothing insulation level can be determined by the observed outdoor temperature from yesterday and the maximum temperature from today's weather forecast. Another study on investigating occupants' clothing insulation levels was executed by De Carli et al. (2007). They found that the outdoor temperature, especially at 6:00 A.M. had a significant impact on people's clothing selection. Furthermore, the indoor temperature would not affect the clothing selection, but had a direct influence on the clothing adjustment behaviour during the working time.

The modelling of human adaptive behaviour with regard to other adaptive opportunities such as operating fans, opening/closing doors and adjusting blinds is usually carried out via actions of opening/closing windows (Nicol and Humphreys 2004; Haldi and Robinson 2009b), in which the outdoor or indoor illuminance level is used as the predictor of blind usage, because a major function of blind is to *"exclude* *glare from outdoors"* (Nicol and Humphreys 2004). Based on specific field studies on blind usage in buildings, Inoue et al. (1988) suggested that the incident distance of direct solar radiation is the main trigger of adjusting blinds. Reinhart (2004) used the incoming direct solar irradiance at the workspace as the trigger of blind usage in a model for predicting manual and automatic control of blinds and lights, and the threshold is 50W/m^2. In addition, the blind will be fully re-opened when occupants first arrive at the office in the morning. In view of thermal comfort, Newsham (1994) introduced a manual blind control algorithm using the sunlight intensity falling on the occupants and the threshold is defined as 233W/m^2. Furthermore, he proposed that if the blind was closed, it would remain in this state until the following morning. Based on field studies carried out in the US, Inkarojrit (2006) found that the probability of blind closing could be modelled using the vertical solar irradiance at windows together with occupants' brightness sensitivity. The same as predicting the operation of windows, Haldi and Robinson (2009b) proposed different predictors of blind usage (raise, lower) based on the time of day (arrival, during presence and departure). They are indoor horizontal illuminance level, lower/upper unshaded fractions and outdoor horizontal illuminance level.

Based on the literature review above, it was found that current models of human adaptive behaviour have not considered the following aspects:

1) Priority of selection from a range of different available adaptive opportunities: even though Rijal et al. (2008) had assumed an order of priority among some adaptive opportunities based on field surveys in Pakistani buildings: door > window > fan, this has not been implemented in the human adaptive behaviour modelling, which is still carried out by separately predicting each adaptive action such as opening windows.

2) Effects from other environmental stimuli: as described by Haldi and Robinson (2009a), the effects from other environmental stimuli such as CO_2, relative humidity, etc. should also be considered during the modelling of human adaptive behaviour in non-air-conditioned buildings. However, this is rarely considered in existing models.

In order to address the above issues, a field survey was carried out in Loughborough University to obtain an understanding of how occupants adjust their surrounding environment in non-air-conditioned buildings through various adaptive opportunities. From this survey, a new approach to modelling human adaptive behaviour is proposed, and is introduced here.

Field survey

The field survey was carried out in Loughborough University, UK (52°45'54''N, 1°14'15''W, alt.70 m), during the summer of 2009. Four buildings inside the University campus, as shown in Figure 1, were selected. The first three are purely naturally ventilated buildings, while the last one is a mixed-mode building. However, the mechanical ventilation system in the mixed-mode building cannot be adjusted by occupants directly. Therefore, the adaptive opportunities provided in these four buildings are similar to those listed in Table 1. In addition, the surveyed offices could be classified into two types as shown in Figure 2: single-occupied office and multi-occupied office (less than 6 occupants).

Figure 1. Surveyed buildings in Loughborough University. a) Wolfson building, b) Administration-2 building, c) Sir Richard Morris building, d) Sir Frank Gibb building.

Table 1. Available adaptive opportunities in surveyed buildings.

Opening/closing windows	Opening/closing doors
Adjusting clothing insulation	Adjusting blinds/curtains
Drinking hot/cool drinks	Changing location
Operating private fans (optional)	

a) b)

Figure 2. Surveyed offices. a) Single-occupied office, b) Multi-occupied office.

The field survey was executed by face-to-face interviews with the building occupants, who were mainly researchers in Loughborough University. The aim of this survey was to obtain information on how occupants in non-air-conditioned buildings maintain their thermal comfort during their work through performing available adaptive actions. The questionnaire was developed based on a thorough literature review of existing research on human adaptive behaviour. The questions covered the following aspects:

1) Background information: gender, occupation, floor, distances to windows and doors, building side, age, country (length of residence in UK if not British);
2) Adaptive behaviour during work: availability and order of preference of adaptive actions when feeling warm, availability and order of preference of adaptive actions when feeling cool, availability and order of preference of actions when experiencing poor indoor air quality, actions when experiencing noise, actions when experiencing glare problem, priority of different environmental stimuli (thermal, acoustic, solar, rain and wind);
3) Clothing preference for work: dress code, priority of factors influencing clothes choice, regular time leaving home for work in the morning, clothing adjustment when first arrive at the office in the morning, mode of transportation;
4) Window/door adjustment when first arrive in the morning: reasons for adjusting windows/doors when first arrive in the morning, priority of opening windows and opening doors;
5) Window/blind adjustment when finishing daily work: allowance of night cooling strategy, preference of using night cooling for weekdays, preference of using night cooling for weekends, blind/curtain adjustment when finishing daily work, blind/curtain adjustment when finishing daily work before weekend.

Survey results

Table 2 lists some statistic information about this field survey.

Table 2. Basic statistic of data of field survey.

Environment	**Classification with the number of participants**
Buildings	Wolfson building (32); Administration-2 building (12); Sir Richard Morris building (26); Sir Frank Gibb building (33)
Distances to windows/doors	Far from windows or doors (25); Near windows and doors (78)
Occupants	**Classification with the number of participants**
Gender	Male (54); Female (49)
Occupations	Academic staff (60); Research associate (4); Research student (24); Support staff (15)
Floor	Ground floor (24); 1st floor (30); 2nd floor (49)
Age	20-29 (22); 30-39 (32); 40-49 (22); 50-59 (15); 60+ (8); Not mention (4)
Origins	UK (60); China (8); Pakistan (6); India (5); Others (24)

The total number of participants in this survey is 103. However, for the analysis of occupants' adaptive preference, only the occupants with easy access to common adaptive opportunities in non-air-conditioned buildings (opening windows; changing clothing insulation; opening doors; adjusting blinds/curtains) were considered. Therefore, the total number of participants considered in the adaptive preference analysis is 77. Figure 3 shows the survey results expressing the priority of occupants' choice of carrying out adaptive actions when they are feeling hot.

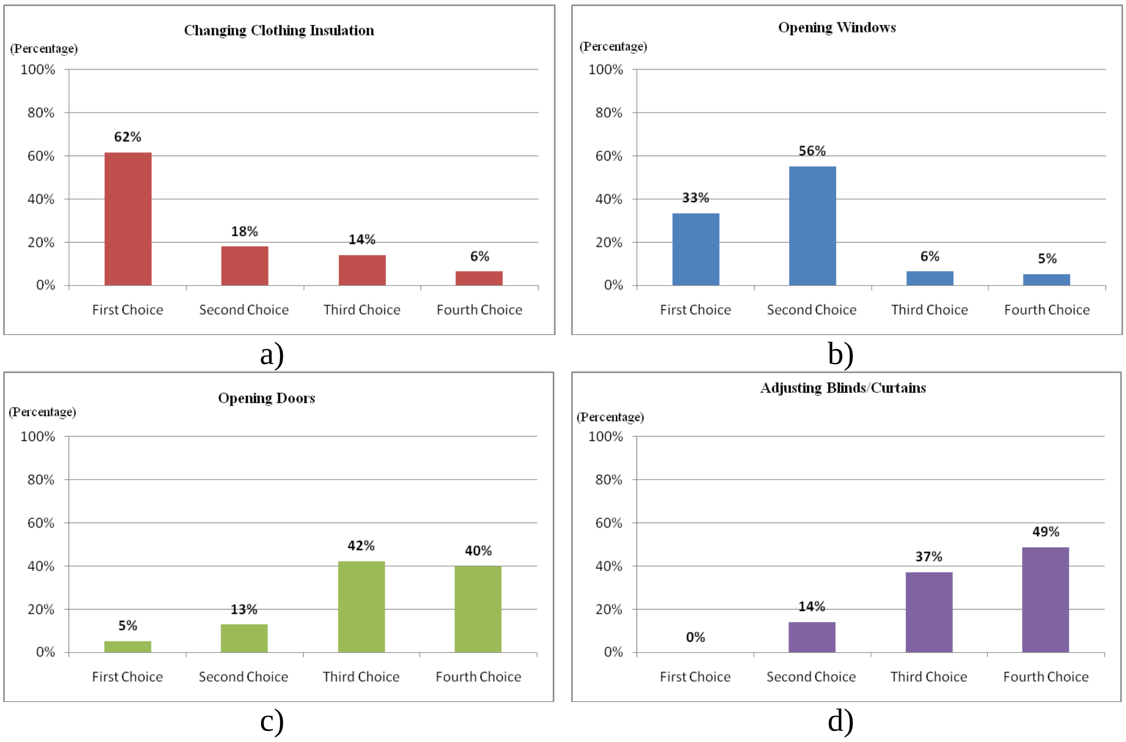
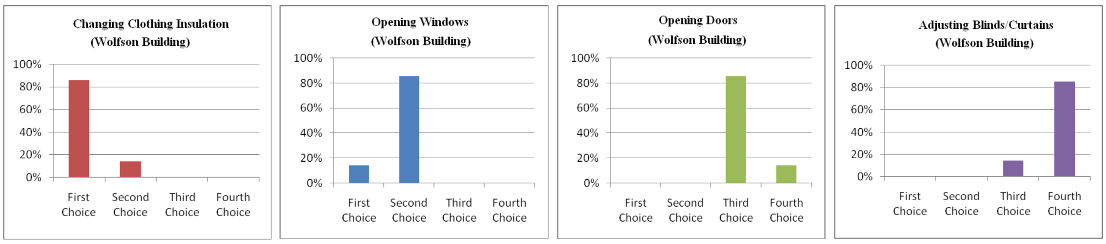


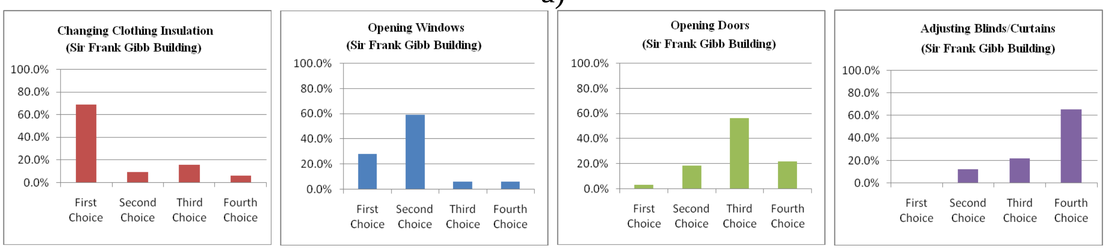
Figure 3. Preference of adaptive actions. a) Changing clothing insulation, b) Opening windows, c) Opening doors, d) Adjusting blinds/curtains.

Figure 3 shows the percentage of people in terms of their order (the first four choices when feeling hot) of taking various adaptive actions. From the results, it was found that occupants have high priorities of changing clothing insulation and opening windows when feeling hot, because more than 80% participants expressed that they would carry out these two actions first, especially changing clothing insulation (62%). However, it is possible for occupants to have different preferences when using available adaptive opportunities, as almost every position in the preference sequence has more than one possibility of adaptive action. For example, the first three adaptive actions are possible to be used as the first choice, except adjusting blinds/curtains. This means that occupants have various preferences when using adaptive opportunities to adjust their surrounding thermal environment. From this survey, the priority is not the same as Rijal proposed from a Pakistan project (Rijal et al. 2008), as he suggested that opening doors had a higher priority than opening windows. This difference is probably because of different types of buildings and outdoor conditions for the survey. However, the findings from this survey could be used to explain why Yun and Steemers (2009) assumed different types of window users (passive, medium and active window users) in the Yun algorithm.

Based on the survey, it was also found that there are other potential factors that have effects on occupants' adaptive preference. Figure 4 shows the comparison among the results of adaptive preference in three buildings (Wolfson building, Sir Frank Gibb building and Sir Richard Morris building). From the comparison, it was easy to find that in the first two buildings, the trend of adaptive preference is the same as shown in Figure 3 (changing clothing insulation has a higher possibility to be carried out at the first choice, followed by opening windows, opening doors and adjusting blinds/curtains separately). However, in the Sir Richard Morris building, the priority of adjusting blinds/curtains is higher than opening doors at the third choice. Based on the explanations from respondents in the survey, two main factors could be considered to affect occupants' adaptive behaviour: working environment and solar gain. During the survey, 7 (27%) respondents in the Sir Richard Morris building expressed that they rarely used the door due to noise from the corridors. Meanwhile, at the southwest side of this building, the indoor thermal environment is greatly influenced by the solar radiation. Therefore, occupants prefer to use the blinds/curtains more than any other sides of the building. This trend could be found from Figure 5 expressing the percentage of offices, in which the occupants chose to use blinds/curtains at a high priority (1st or 2nd choice), in terms of building sides. The results show that the offices facing southwest have higher probabilities to suffer from strong solar radiation, and blinds/curtains are used more in these offices.



a)



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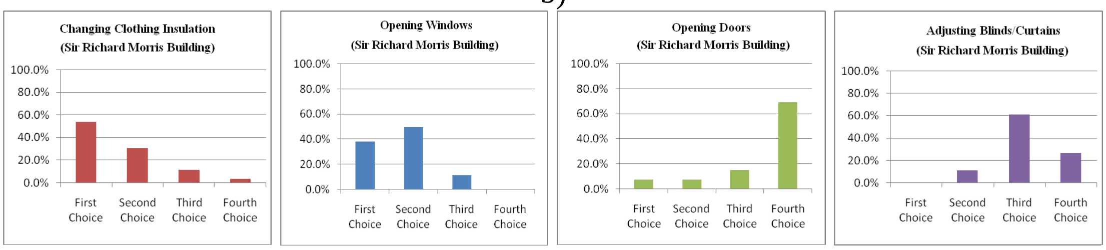


c)

Figure 4. Preference of adaptive actions in three buildings: a) Wolfson Building, b) Sir Frank Gibb Building, c) Sir Richard Morris Building.

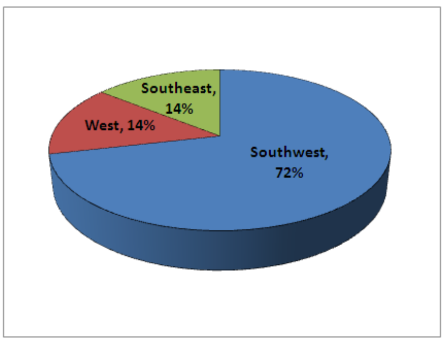


Figure 5. Effect from building sides on using blinds/curtains.

Modelling of human adaptive behaviour

Based on the findings from this survey, a new approach modelling human adaptive behaviour in non-air-conditioned buildings is proposed and described in this paper. Compared with existing human behaviour models, this Human Adaptive Behaviour model (HAB model) considers occupants' orders of preference when performing various adaptive actions to maintain their thermal comfort together with the effects from other environmental stimuli such as indoor air quality, noise level and solar radiation on occupants' adaptive behaviour.

Application of the HAB model

The purpose of the human behaviour modelling is to predict occupants' adaptive actions triggered by various discomfort sensations, which are usually represented by specific environmental parameters such as indoor temperature (Nicol and Humphreys 2004) or outdoor temperature (Haldi and Robinson 2009a) in building performance simulation. For this purpose, the application of the HAB model is defined in Figure 6. At every time step (t) in the building performance simulation, the program will simulate the building performance based on predefined climate data and boundary conditions of modelled buildings. The HAB model aims to modify specific boundary conditions of buildings such as the states of windows or doors. Therefore, it will determine the boundary conditions for the next simulation time step (t+1) according to corresponding environmental parameters derived from the main simulation procedure. In addition, if the adaptive action with regard to changing clothing insulation was executed, a modified clothing insulation value should be sent back to the main simulation procedure to improve the prediction of thermal comfort.

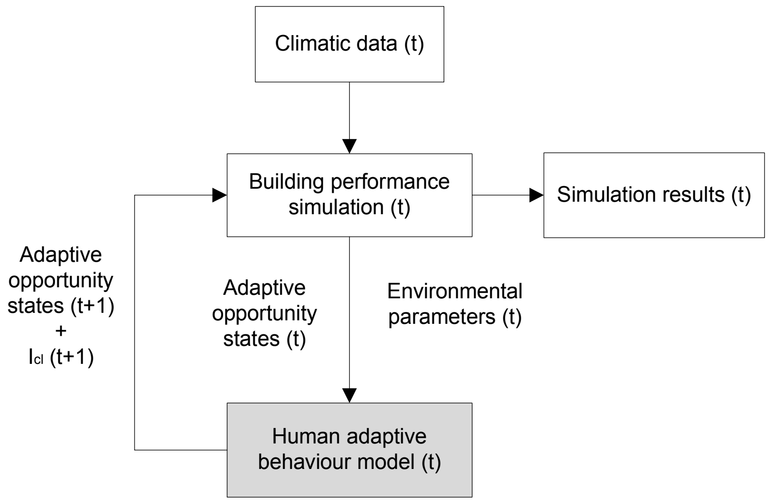


Figure 6. Application of the HAB model.

Structure of the HAB model

The HAB model mainly consists of three separate models (adaptive preference model, occupancy scheduling model and behaviour determining model) defined in three grey boxes in Figure 7. The same as the model proposed by Haldi and Robinson (2009a), the occupancy scheduling model and behaviour determining model play a very important role in the HAB model for predicting human adaptive behaviour. In order to reflect the relationship between available adaptive opportunities in non-air-conditioned buildings, an adaptive preference model is proposed. This model will be invoked at the beginning of the simulation to set a specific adaptive preference for each occupant. This adaptive preference will be retained by that occupant for the whole simulation procedure. Before determining the human adaptive behaviour at every simulation time step, the occupancy scheduling model is invoked to determine the occupation of the simulated room. If the room is not occupied, it means that no adaptive action is possible to happen, and then the HAB model will return the current states of adaptive opportunities to the main simulation procedure. If the room is occupied, the behaviour determining model will predict the human adaptive behaviour according to the current states of adaptive opportunities and related environmental parameters derived from the main simulation procedure. Three sub-models should be used for different time of day (arrival, intermediate, departure). If specific adaptive action was predicted to occur, then the corresponding state of adaptive opportunity will be modified, and the modified set of values will be sent back to the main simulation procedure for the next simulation time step.

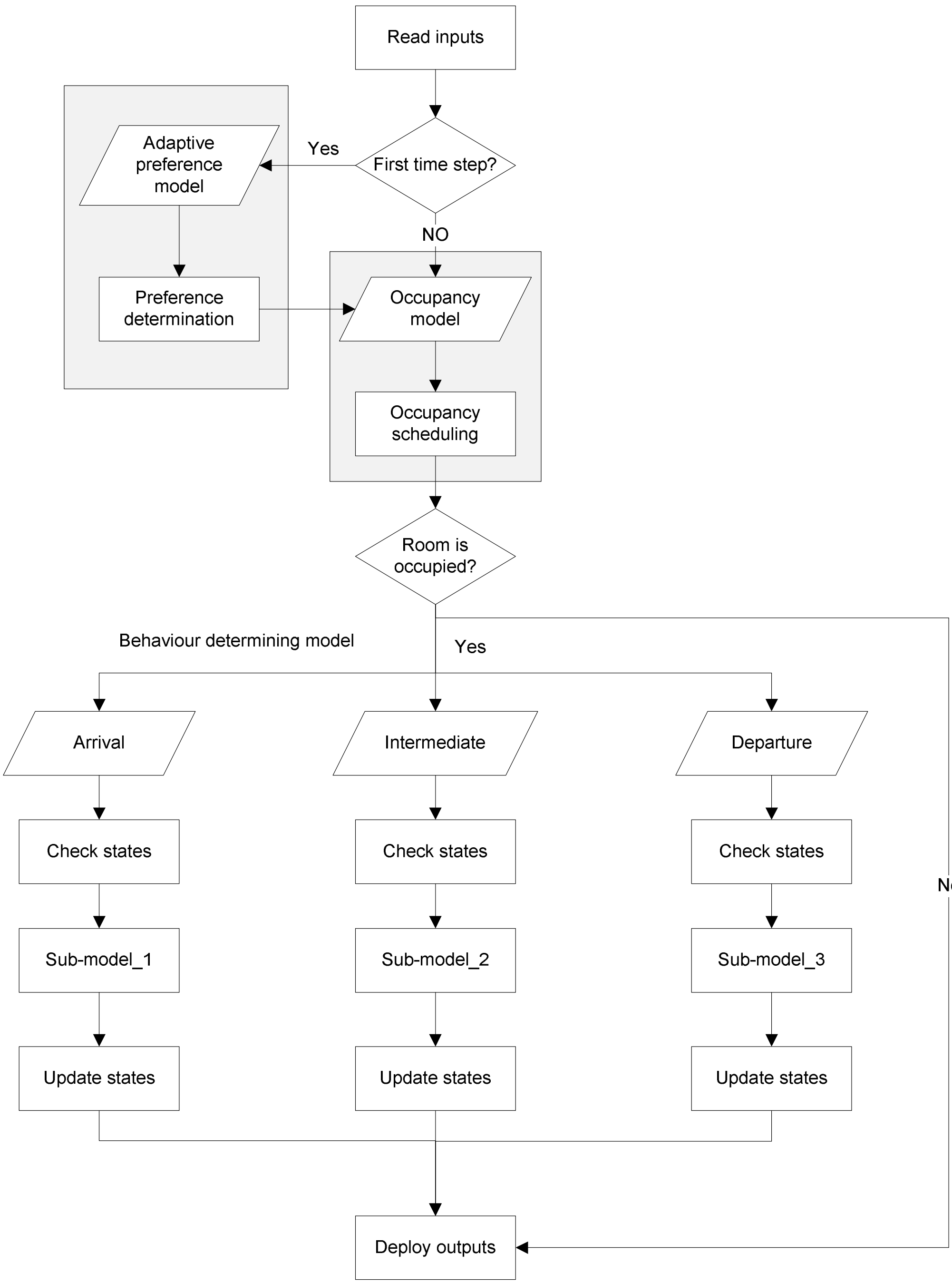


Figure 7. Flow chart of the HAB model.

Modelling of adaptive preference

It is difficult to predict the adaptive preference of an individual occupant in non-air-conditioned buildings. However, it is possible to determine a proportion of different adaptive preferences for a group of people such as most people will take off extra clothes first when feeling hot, followed by opening windows, opening doors and adjusting blinds/curtains. Therefore, the probabilistic method is chosen as the modelling approach to predict adaptive preferences of building occupants. The tree diagram of occupants' adaptive preference due to warm feelings in summer is shown in Figure 8 based on the data from the field survey:

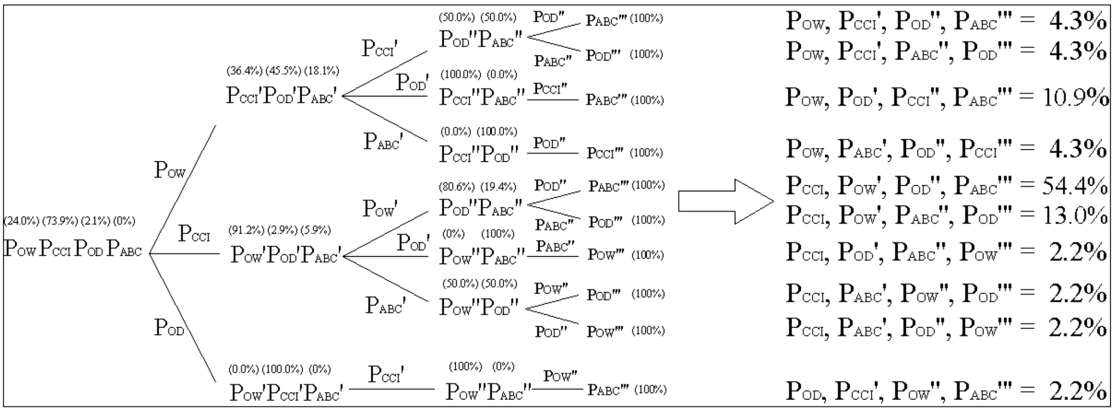


Figure 8. Tree diagram of occupants' adaptive preference.

where

$P_{OW}, P_{OW}^{'}, P_{OW}^{''}, P_{OW}^{'''}$: Probabilities of opening windows;

$P_{CCI}, P_{CCI}^{'}, P_{CCI}^{''}, P_{CCI}^{'''}$: Probabilities of changing clothing insulation;

$P_{OD}, P_{OD}^{'}, P_{OD}^{''}, P_{OD}^{'''}$: Probabilities of opening doors;

$P_{ABC}, P_{ABC}^{'}, P_{ABC}^{''}, P_{ABC}^{'''}$: Probabilities of adjusting blinds/curtains.

At the beginning of the simulation, the adaptive preference model will assign a specific adaptive preference for each occupant based on the probability distribution defined in Figure 8. This means that if the occupant feels hot, s/he will carry out adaptive actions according to a specific sequence during the simulation.

Dynamic modelling of adaptive behaviour

As has been adopted by many researchers (Fritsch et al. 1990, Yun and Steemers 2009, Haldi and Robinson 2009a), the Markov process is also used as the basic approach in the HAB model for the modelling of human adaptive behaviour. This means that the state of the next time step only depends on its current state, as expressed by Equation 1:

$$P(X_{t+1} = i | X_t = j, X_{t-1} = k, ..., X_{t-N} = l) = P(X_{t+1} = i | X_t = j) =: T_{ij}(t) \qquad (1)$$

In addition, the transition probability functions between states (T_{ij}) could be defined using logit distributions (Equation 2) expressing the relationship between the probability of adaptive action happening (p) and specific triggers (x).

$$p = e^{(a+bx)} / (1 - e^{(a+bx)}) \qquad (2)$$

Modelling of interactions among potential triggers
Occupants will adjust their indoor environment due to different discomfort sensations. In real conditions, it is possible that occupants experience more than one discomfort sensation simultaneously, such as it is noisy outdoors but they are feeling hot indoors. Under these conditions, conflicts on executing specific adaptive actions (such as opening a window) will become apparent. One possible way to solve this problem is using fuzzy logic theory that is developed for control systems. This method has been adopted for controlling indoor thermal environments by many researchers (Dounis et al. 1995; Eftekhari and Marjanovic 2003). In this method, the system is controlled by many linguistic control rules derived from experimental knowledge, and expressed in **IF-THEN** form. In the HAB model, these linguistic control rules could be defined based on the degree of effect from each environmental trigger, for example:

IF 'Very hot indoors' **AND** 'Slightly noisy outdoors' **THEN** 'Open the window'.

Figure 9 shows different combinations of potential triggers using a Venn diagram:

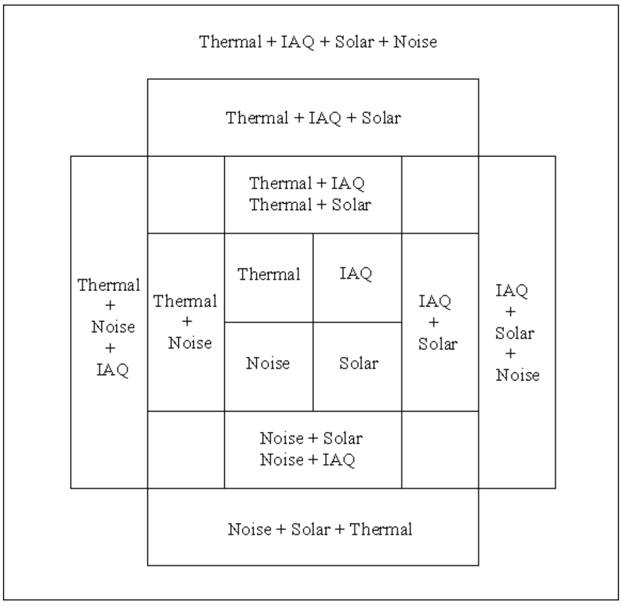


Figure 9. Combinations of potential triggers of adaptive actions.

Model application
Based on the flow chart shown in Figure 7, the programming code of the HAB model has been preliminarily developed in Matlab. The adaptive preference model was developed based on the field survey, and the operation of the current HAB model still need to use some reasonable assumptions that would be determined in the future research:

1. PMV is preliminarily used as the predictor of thermal discomfort;
2. The occupants are always in the offices from 9:00 A.M. to 5:00 P.M.;
3. Two levels of clothing insulation for daily work (Lower: 0.5clo, Higher: 0.8clo);
4. Priority of different triggers: Too warm < Noisy, Too warm < Strong outdoor wind, Poor indoor air quality < Noisy, Too cool < Glare;
5. Occupants will take off their outer layer of clothes when first arrive at the office in the morning;

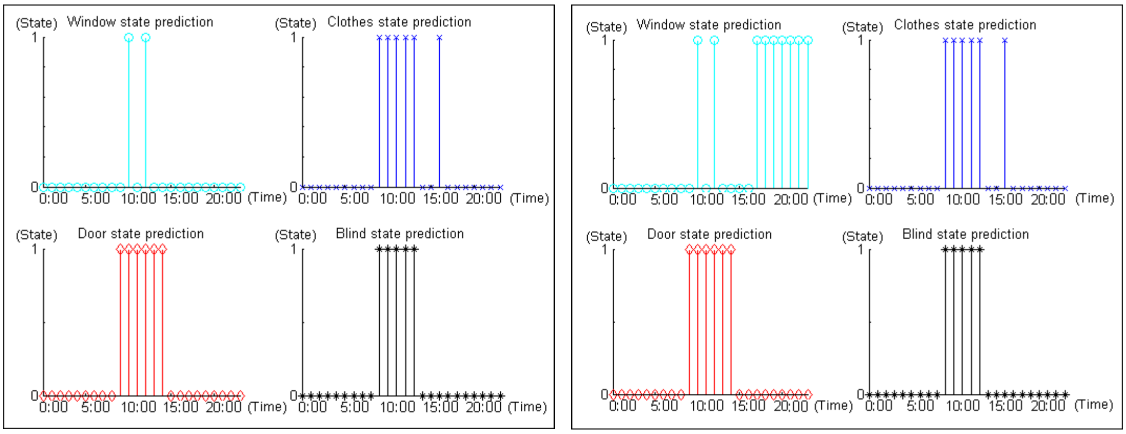
6. The operation of blinds/curtains is triggered by the illuminance level at workspace during the working time;
7. After daily working time, windows are always closed for offices on the ground floor, 27% of windows will be kept open for night cooling for non-ground floor offices;
8. After daily working time during weekdays, blinds are open, but will be closed during the weekend for all offices.

At present, the required inputs to the HAB model, as listed in Table 3, are generated from a piece of Matlab code.

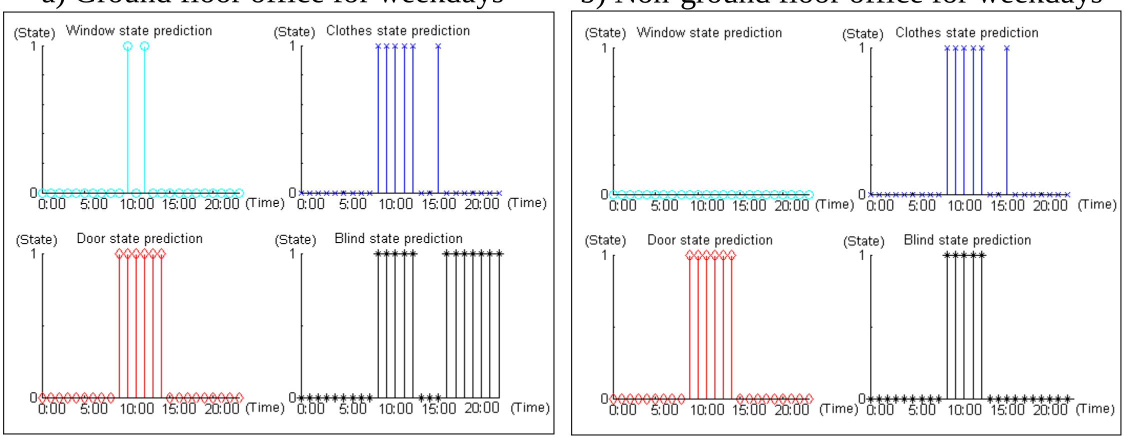
Table 3. Inputs of the HAB model.

PMV	Illuminance level	Noise level	CO_2 concentration
Wind speed outdoors	Day (Mon - Sun)	Floor number	Window operability
Permission of night cooling strategy			

Some simulation results are shown in Figure 10, in which ‘0’ means the corresponding adaptive action is not executed such as the window remains closed; while ’1’ means the corresponding adaptive action is executed such as the window is opened. The time interval is set as 1 hour to show how the HAB model works under different conditions.



a) Ground floor office for weekdays b) Non-ground floor office for weekdays



c) Blind operation on Fridays d) Window operation is restricted

Figure 10. Prediction of human adaptive behaviour under different conditions. a) Ground floor office, b) Non-ground floor office, c) Blind operation on Fridays, d) Window operation is unable.

Figure 10-a shows the simulation result of ground floor offices for weekdays without any restriction of adaptive actions. Figure 10-b shows the result of non-ground floor offices using night cooling strategy for weekdays. Figure 10-c shows the result of blind operation on Fridays. Figure 10-d shows the result of offices, in which the window operation is restricted.

Discussion

This paper expresses a possible way to study human adaptive behaviour in non-air-conditioned buildings based on a statistical method. Due to the limited surveying period (only summer time), the current sample size is not large enough to provide a reliable simulation result that could be used in building performance simulation. However, a number of valuable trends and potential influencing factors have been found from the field survey. To provide some useful information for the future study, the anticipant sample size was calculated based on the results from this field survey using Equation 3 (Bowerman et al. 2004):

$$n = p(1-p)\left(\frac{Z_{\alpha/2}}{B}\right)^2 \qquad (3)$$

where

n: Sample size

p: Percentage of population picking a choice

B: Confidence interval

$Z_{\alpha/2}$: Z-value (1.96 for 95% confidence level - $Z_{.025}$)

Based on the proportion expressed in Figure 8, the current result has a maximum value of confidence interval 11.0%, and a minimum value 3.2%. To obtain a more accurate result (confidence level: 95.0%, confidence interval: 5.0%), the anticipant sample size is 370, therefore, more surveys need to be done in the coming summer.

At present, the basic programming of the HAB model has been implemented in Matlab based on and findings from the field survey and some reasonable assumptions. However, more field studies have to be carried out for the continuously development of the HAB model such as determining the relationship between environmental triggers (indoor temperature, outdoor temperature, noise level, etc.) or discomfort sensations (thermal discomfort, visual discomfort, acoustic discomfort or perceived poor indoor air quality) and human adaptive behaviour. Because the programming of this model is based on the block-based method, it is easy to replace the code of pre-made assumptions based on the results from future studies.

Conclusions

This paper has introduced a probabilistic approach to modelling human adaptive behaviour with the consideration of occupants' order of preferences using various adaptive opportunities together with the effects from other environmental factors such as visual environment, acoustic environment and indoor air quality. This model is currently operating based on some assumptions that will be improved continuously, as more field studies are going to be carried out during the coming two years.

Some useful findings from a field survey carried out in Loughborough University, UK, in the summer, 2009, have also been presented in this paper and implemented in the HAB model. It was found that such adaptive actions as opening windows and changing clothing insulation level have much higher priorities than other ones such as opening doors and adjusting blinds/curtains. However, other possibilities with different order of priority also exist for occupants. It means that occupants have variable orders of adaptive preferences in real applications, even working in similar environments. In addition, the working environment and solar radiation, as might be expected, tends to have effects on occupants' adaptive preferences such as the usage of doors and blinds.

More surveys will be conducted to increase the sample size to provide a more reliable result for the prediction of human adaptive behaviour. However, this preliminary study is essential for testing the proposed new methodology of capturing human adaptive behaviour from occupant survey data. This study provides several valuable results, based on which some basic trends have been indicated, though more surveys are needed for greater reliability.

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References

ASHRAE (2004), ASHRAE Standard 55-2004: Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

Baker, N. and Standeven, M. (1997), A Behavioural Approach to Thermal Comfort Assessment. International Journal of Solar Energy, Vol. 19, No. 1, pp 35.

Bowerman, B.L., O'connell, R.T. and Orris, J.B. (2004), Essentials of Business Statistics. United States: The McGraw-Hill Companies, Inc.

Brager, G.S. and de Dear, R.J. (1998), Thermal adaptation in the built environment: a literature review. Energy and Buildings, Vol. 27, pp 83-96.

CIBSE (2006), CIBSE Guide A: Environmental Design. The Chartered Institution of Building Services Engineers, UK.

de Carli, M., Olesen, B.W., Zarrella, A. and Zecchin, R. (2007), People's clothing behaviour according to external weather and indoor environment. Building and Environment, Vol. 42, No. 12, pp 3965-3973.

de Dear, R.J. and Brager, G.S. (2002), Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings, Vol.34, No. 6, pp 549-561.

de Dear, R.J. and Brager, G.S. (1998), Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, Vol. 104, No. 1, pp 145-167.

Dounis, A.I., Santamouris, M.J., Lefas, C.C. and Argiriou, A. (1995), Design of a fuzzy set environment comfort system. Energy and Buildings, Vol. 22, pp 81-87.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2008), BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers, and Contractors. John Wiley & Sons, Inc., US.

Eftekhari, M.M. and Marjanovic, L.D. (2003), Application of fuzzy control in naturally ventilated buildings for summer conditions. Energy and Buildings, Vol. 35, No. 7, pp 645-655.

Fanger, P.O. (1970), Thermal Comfort. Danish Technical Press, Copenhagen.

Fishman, D.S. and Pimbert, S.L. (1982), The thermal environment in offices. Energy and Buildings, Vol. 5, pp 109-116.

Fritsch, R., Kohler, A., Nygård-ferguson, M. and Scartezzini, J. (1990), A stochastic model of user behaviour regarding ventilation. Building and Environment, Vol. 25, No. 2, pp 173-181.

Haldi, F. and Robinson, D. (2009a), A comprehensive stochastic model of window usage: Theory and Validation, Proceedings of the Building Simulation Conference, Glasgow, Scotland, July 27-30 2009.

Haldi, F. and Robinson, D. (2009b), A comprehensive stochastic model of blind usage: Theory and Validation, Proceedings of the Building Simulation Conference, Glasgow, Scotland, 27-30 July 2009.

Haldi, F. and Robinson, D. (2008a), A comparison of alternative approaches for the modelling of window opening and closing behaviour, Proceedings of Air Conditioning and the Low Carbon Cooling Challenge, London, UK, 27-29 July 2008.

Haldi, F. and Robinson, D. (2008b), On the behaviour and adaptation of office occupants. Building and Environment, Vol. 43, No.12, pp 2163-2177.

Herkel, S., Knapp, U. and Pfafferott, J. (2008), Towards a model of user behaviour regarding the manual control of windows in office buildings. Building and Environment, Vol. 43, No. 4, pp 588-600.

Humphreys, M.A. and Nicol, J.F. (1998), Understanding the adaptive approach to thermal comfort. ASHRAE Transactions, Vol. 104, No. 1B, pp 991-1004.

Inkarojrit, V. (2006), Developing predictive Venetian blinds control models using visual comfort predictors, Proceedings of the PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006, .

Inoue, T., Kawase, T., Ibamoto, T., Takakusa, S. and Matsuo, Y. (1988), The development of an optimal control system for window shading devices based on investigations in office buildings. ASHRAE Transactions, Vol. 94, No. 2, pp 1034-1049.

ISO (2005), International Standard 7730: Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort. International Standard Organization, Geneva, Switzerland.

McCartney, K.J. and Nicol, J.F. (2002), Developing an adaptive control algorithm for Europe. Energy and Buildings, Vol. 34, No. 6, pp 623-635.

Morgan, C. and de Dear, R.J. (2003), Weather, clothing and thermal adaptation to indoor climate. Climate Research, Vol. 24, pp 267-284.

Newsham, G.R. (1994), Manual control of window blinds and electric lighting: implications for comfort and energy consumption. Indoor Environment, Vol. 3, pp 135-144.

Nicol, J.F., Raja, I.A., Allaudin, A. and Jamy, G.N. (1999), Climatic variations in comfortable temperatures: the Pakistan projects. Energy and Buildings, Vol. 30, No.3, pp 261-279.

Nicol, J.F. and Humphreys, M.A. (2004), A stochastic approach to thermal comfort - Occupant behaviour and energy use in buildings. ASHRAE Transactions, Vol. 110(Part 2), pp 554-568.

Reinhart, C.F. (2004), Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. Solar Energy, Vol.77, pp 15-28.

Rijal, H.B., Humphreys, M.A. and Nicol, J.F. (2009), Understanding occupant behaviour: the use of controls in mixed-mode office buildings. Building Research & Information, Vol. 37, No. 4, pp 381-396.

Rijal, H.B., Tuohy, P., Humphreys, M.A., Nicol, J.F., Samuel, A., Raja, I.A. and Clarke, J. (2008), Development of adaptive algorithms for the operation of windows, fans, and doors to predict thermal comfort and energy use in Pakistani buildings. ASHRAE Transactions, Vol. 114, No. 2, pp 555-573.

Rijal, H.B., Tuohy, P.G., Nicol, J.F., Humphreys, M.A. and Clarke, J.A. (2007a), A window opening algorithm and UK office temperature: Field results and thermal simulation, Proceedings of Building Simulation 2007, Beijing, China, 3-6 September 2007.

Rijal, H.B., Tuohy, P., Humphreys, M.A., Nicol, J.F., Samuel, A. and Clarke, J. (2007b), Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy and Buildings, Vol. 39, No. 7, pp 823-836.

Yun, G.Y., Tuohy, P. and Steemers, K. (2009), Thermal performance of a naturally ventilated building using a combined algorithm of probabilistic occupant behaviour and deterministic heat and mass balance models. Energy and Buildings, Vol. 41, No. 5, pp 489-499.