Adaptive thermal comfort and its application in mixed mode buildings: The case of a hot-summer and cold-winter climate in China

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14th November 2018

This dissertation is submitted to the University of Cambridge for the degree of Doctor of Philosophy

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text
Abstract

It is widely recognised that one’s ability of adaptation is remarkable and thermal comfort is significantly related to such adaptations. This study proposes an alternative method of predicting adaptive thermal comfort based on the availability of adaptations, in particular behavioural adaptations, which needs quantifications of individual adaptation processes and of interactions between them. The fundamental argument of this method is that exercising an adaptive behaviour leads to an increase in comfort temperature, which is termed adaptive increment in this study. Apart from adaptive increments, this method also determines a baseline thermal comfort temperature (the thermal comfort temperature without adaptations) and a correction factor that considers the factors affecting adaptive behaviours, based on which, the highest operative temperature at which people may still feel thermally comfortable. This may be applied in mixed mode (MM) buildings to achieve a higher air-conditioning (AC) setpoint which may lead to a significant reduction in cooling energy.

This method is believed to be flexible in dealing with different environments with various levels of adaptations and likely to be advantageous over the steady-state and adaptive models in predicting thermal comfort temperature of an environment with abundant adaptive opportunities. This study also evaluates ways of promoting the use of adaptive opportunities. It explores how adaptive thermal comfort theories may be used for behaviour modelling and in turn be applied to enhance the energy performances and comfort levels of real buildings. To improve the feasibility of this method key effective adaptive behaviours are studied in detail through lab experiments and field studies.

The lab experiment has found the adaptive increment of taking cold water to be 1.5°C which is more significant than the previous literature suggests. When all the studied adaptive behaviours are exercised, the overall adaptive increment is as high as 4.7°C. However, the research has identified some issues associated with the adaptive opportunities studied. These include the existence of constraints on the use of adaptive behaviours, the low availability of some effective adaptive opportunities, the low operation frequency of desk fans and the
misuse of windows and AC systems. Despite this, the availability of more adaptive opportunities has been verified to be capable of increasing the highest operative temperature at which people may still feel thermally comfortable: the lab experiment shows that over 80% of the participants can still find it thermally comfortable at an operative temperature of 30°C on the condition that adequate adaptive opportunities are provided; the field study shows that the thermal comfort temperature of occupants increases by at least 1°C when desk fans and cool mats are available.

Based on these analyses, it proposes an MM system which encourages occupants to exercise adaptive opportunities and improves both comfort levels and energy efficiency. Building performance simulation results show that the proposed MM system is effective in reducing the reliance on AC systems and promotes effective uses of windows and AC systems. By applying the MM system and the associated passive energy-saving strategies, an office can cut cooling energy by about 90% and the peak cooling load by over 80% during transitional seasons.
Acknowledgement

I would first like to thank Professor Koen Steemers who has provided me with valuable guidance and useful advice. His valuable insights enlighten me not only in this thesis but also in future work.

Thank you to my every colleague in the Department of Architecture, University of Cambridge, for making this great environment to be part of.

I would like to thank Professor Yingxin Zhu, as well as Professor Yinxin Zhu and Dr Qin Ouyang, for the use of and help with respectively, the Climate Chamber at the Department of Architecture, Tsinghua University.

Last but not least, I would like to thank my family for their support, love and encouragement.
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List of Acronyms

AC - Air Conditioning
BMS - Building Management System
CO₂ - Carbon Dioxide
cw - cold water
ESP-r - Environmental System Performance research
FPFA - Fan-coil Plus Fresh Air
HVAC - Heating, Ventilation and Air Conditioning
kW - kilo Watt
kWh - kilo Watt hour
ISO - International Standardization Organization
MM - Mixed Mode
MV - Mechanical Ventilation
ncw - no cold water
NV - Natural Ventilation
PMV - Predictive Mean Vote
ppm - parts per million
RPM - Rotation Per Minute
SET* - Standard Effective Temperature
SCATs - Smart Controls and Thermal Comfort
TNZ - Thermoneutral Zone
TSV - Thermal Sensation Vote
VAV - Variable Air Volume
VRF - Variable Refrigerant Flow
# Nomenclature

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>The specific heat of air</td>
<td>$[\text{kJ/(kg}^\circ\text{C})]$</td>
</tr>
<tr>
<td>$h$</td>
<td>height</td>
<td>$[\text{m}]$</td>
</tr>
<tr>
<td>$m$</td>
<td>The Mass flow rate of supply air</td>
<td>$[\text{kg/s}]$</td>
</tr>
<tr>
<td>$p_{\text{AC}}$</td>
<td>The probability of AC usage</td>
<td>$[%]$</td>
</tr>
<tr>
<td>$P_{\text{cool mat}}$</td>
<td>The probability of cool mat usage</td>
<td>$[%]$</td>
</tr>
<tr>
<td>$P_{\text{fan}}$</td>
<td>The probability of fan usage</td>
<td>$[%]$</td>
</tr>
<tr>
<td>$P_{\text{win}}$</td>
<td>The probability of window open</td>
<td>$[%]$</td>
</tr>
<tr>
<td>$Q$</td>
<td>The peak cooling load</td>
<td>$[\text{kW}]$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Significance value</td>
<td>$[-]$</td>
</tr>
<tr>
<td>$T_{\text{in}}$</td>
<td>Indoor air temperature</td>
<td>$[^\circ\text{C}]$</td>
</tr>
<tr>
<td>$T_{\text{out}}$</td>
<td>Outside air temperature</td>
<td>$[^\circ\text{C}]$</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume flow rate</td>
<td>$[\text{m}^3/\text{s}]$</td>
</tr>
<tr>
<td>$V_{10}$</td>
<td>Wind speed measured at the meteorological site at the standard height of 10 m</td>
<td>$[\text{m/s}]$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density</td>
<td>$[\text{kg/m}^3]$</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference between the setpoint and the temperature of the supply air from cooling coil</td>
<td>$[^\circ\text{C}]$</td>
</tr>
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Chapter 1 - Introduction

In the summer-hot and winter-cold zone of China, AC systems are highly relied on for cooling. However, during the transitional seasons from spring to summer or from summer to autumn, cooling energy requirements can be largely reduced by properly using external air to cool down the building. Also, due to the rise in the demand for good indoor air quality in China, natural or mechanical ventilation should be carefully designed to meet the fresh air requirements. Hence, a well-designed mixed mode (MM) building can play an important role in energy conservation and comfort improvement for the climate. An MM building enables natural ventilation (NV) for cooling when outside conditions are favourable and relies on air conditioning (AC) systems for cooling in extreme conditions. The changeover between NV mode and AC mode requires an appropriated changeover temperature which can be determined by analysing the upper thermal comfort temperature of occupants. The hot-summer and cold-winter zone in China has the feature that there are considerably long transitional seasons during which MM buildings may play an important role, and therefore is of interest for this study. Another reason why this area was chosen is that the author is familiar with this area and could more conveniently hire a proper laboratory, select suitable field study sites, recruit enough experimental participants and obtain local climate data.

Thermal comfort of an occupant is influenced by a variety of thermal and non-thermal stimuli, not all of which are fully understood or can be easily quantified, and therefore it seems unlikely to merely rely on a simple comfort model to accurately evaluate one’s thermal comfort, not to mention that there are considerable individual differences. Even so, a thermal comfort model is an important tool to provide guidance in designing a building or building services systems. Currently widely used thermal comfort models include steady-state models, such as Fanger’s PMV model (Fanger, 1970), and adaptive comfort models, such as the one introduced by de Dear et al. (1997). Fanger’s PMV model uses six environmental and personal factors to predict thermal sensations and an adaptive comfort mode forms a linear relationship between outdoor temperatures and indoor thermal comfort temperatures.
It is widely recognised that occupants’ abilities to adapt their environment are powerful factors in determining thermal comfort (Baker and Standeven, 1996; de Dear and Cooper, 1997; Brager and de Dear, 1998; Fanger and Toftum, 2002; Haldi and Robinson, 2008). However, both steady-state models and adaptive comfort models do not explicitly deal with the processes through which occupants adapt to their environment. This study proposes an alternative way to determine adaptive thermal comfort based on the availability of adaptations, in particular behavioural adaptations, which needs quantifications of individual adaptation processes and of interactions between them. The adaptive increment, which was first introduced in Baker and Standeven (1996), is used as the measurement criteria for the quantifications of adaptations. An adaptive increment can be defined as an increase in comfort temperature due to a positive adaptive process. Baker and Standeven (1996) and Oseland et al. (1998) proposed that adaptive increments resulted from different adaptations can be added together for simplicity. However, it is clear that this simplification is not robust. For example, an occupant with low ‘clo’ values will be more susceptible to adjustments in air movement. Hence, this study investigates not only individual adaptation processes but also the interactions among them.

Since various environments provide occupants with different combinations of adaptive opportunities and the combined effects of adaptive opportunities may not be easily derived from assessing individual ones, a thorough investigation on adaptive thermal comfort is conducted by using theoretical studies, lab experiments, surveys and field studies. It also explores the highest operative temperature at which people may still feel thermally comfortable under the experimental conditions, as well as the preferences for various adaptive behaviours. Additionally, based on the adaptive thermal comfort studies and the analysis of existing MM buildings, it proposes an MM system which encourages occupants to exercise adaptive opportunities and improves both comfort levels and energy efficiency.
1.1 Research aim and objectives

This research aims to demonstrate that adaptations, in particular behavioural adaptations, can be quantified and applied in mixed mode systems to improve building energy performances and thermal comfort levels.

The following research objectives serve to realise the above research aim:

- Quantify the benefits of each adaptation and study the factors affecting them through theoretical studies.
- Verify the quantitative evaluations of the adaptations and their interactions through lab experiments and field studies.
- Survey the availability of adaptive opportunities in existing buildings and occupants’ perceptions of adaptations.
- Seek ways of promoting the use of adaptive opportunities and explore how the results of adaptive thermal comfort studies may be used in behaviour modelling and, in turn, be applied to enhance energy performances and comfort levels of real buildings.
- Explore the highest operative temperature at which people may still feel thermally comfortable when abundant adaptive opportunities are provided and study its applications in MM buildings.
- Propose an MM system which encourages occupants to exercise adaptive opportunities and improves both comfort levels and energy efficiency.
- Conduct building performance simulations on the proposed MM system to evaluate its performances.

Research questions of this study are as follows:

- Do people’s adaptations play an important role in indoor thermal comfort and how the adaptations may be quantified?
- Can thermal comfort levels be predicted by using an alternative method based on the quantifications of adaptations?
• How the alternative method of predicting thermal comfort and other adaptive theories can be applied to the design of energy-efficient MM buildings?

• To what extent a well-designed MM building may contribute to thermal comfort improvement and energy conservation?

1.2 Research methodologies
This section summarises the methodologies used to achieve and answer the above research objectives and research questions. The methodologies will be introduced in more detail in the following chapters.

Firstly, a theoretical study on the quantification of behaviours adaptations was conducted via a thorough analysis of previous literature, the SET* model and CFD simulations. CFD simulations were conducted on an office environment to explore how physical conditions of the environment would be affected by exercising adaptive behaviours. The interactions among adaptive behaviours were also quantified by using the SET* model and CFD simulations.

Secondly, a lab experiment was conducted in a climate chamber to verify and develop the results obtained from the theoretical study. This study was divided into a dynamic study and a static temperature study. The former contains an experiment in which air temperature is gradually increasing, whereas the latter looks at several environmental conditions with different fixed air temperatures and various sets of adaptive behaviours. Eight separate experiments with different setups were conducted and each experiment was involved with around 20 participants.

Thirdly, a survey on office adaptive behaviours of subjects in East China was conducted in the form of an online questionnaire which was created by using Wenjuanxing, a widely used online questionnaire system in China. The link to the questionnaire was sent to personal WeChats (a widely used social app in China) or WeChat groups of targeting subjects, and a total of 131 completed questionnaires were received. All the respondents are from Shanghai
Municipality or Zhejiang Province, both of which belong to East China, enjoying a hot-summer and cold-winter climate. As shown in Appendix 5.1, a total of 13 questions are included in the questionnaire. The first question is about the type of office that subjects use, and questions 2-9 concern the available adaptive opportunities in offices. Questions 10-12 evaluate office users’ perceptions and habits with regard to window operations and the last question analyses the perceived effectiveness of 12 adaptive opportunities in thermal comfort improvement.

Fourthly, field studies were conducted in the city of Ningbo in East China to provide practical guidelines to the alternative method of predicting adaptive thermal comfort studied in the theoretical and laboratory studies, and to analyse how office users exercise adaptive behaviours in practice. Thermal comfort levels and behaviours of four participants were studied in detail via monitors, surveys and interviews. The stochastic models of using AC, windows, desk fans and cool mats were also developed to find out the issues associated with the adaptive opportunities and how the availability of other adaptive behaviours affects the use of AC and windows.

Finally, an MM system, which integrates automatic controls over an advanced window system, a signalling system and an associated HVAC system, was proposed. This MM system was studied by using buildings performance simulations to demonstrate to what extent an MM system may contribute to thermal comfort improvement and energy conservation in buildings. A total of thirteen simulation scenarios with different levels of adaptive opportunities and various settings of the HVAC and advanced window systems were proposed.

1.3 Structure of the thesis
Chapter 2 firstly provides a detailed review of psychological and physiological adaptations. It then identifies the pros and cons of currently widely used thermal comfort models. It also looks at theoretical backgrounds of applications of adaptive increments and mixed mode (MM) buildings and effective passive energy-saving strategies that can be applied in MM buildings.
Chapter 3 analyses behavioural adaptations in detail and proposes an alternative method of predicting adaptive thermal comfort. It mainly focuses on quantifying the effectiveness of individual adaptive behaviours and evaluates the factors affecting them. The adaptive increment, the main component of the alternative method of predicting adaptive thermal comfort, is used for the quantification and derived via analysis of previous literature, the SET* model and CFD simulations. The adaptive increment, which was first introduced in Baker and Standeven (1996), is defined as an increase in comfort temperature resulted from exercising an adaptive opportunity.

In Chapter 4, a series of experiments were conducted in a climate chamber to quantitively study the relationships between thermal comfort and adaptations, in particular behavioural adaptations. It attempts to validate the adaptive increments obtained in Chapter 3 and test the application of the alternative method of predicting adaptive thermal comfort. The preferences of individuals for various adaptive behaviours were also evaluated.

Chapter 5 reports on an online survey regarding adaptive opportunities in offices. The survey revealed the availability of adaptive opportunities in offices as well as occupants’ perceptions and habits on using these adaptive opportunities. The results of the survey were used to tailor the subsequent field studies.

In Chapter 6, field studies are conducted to verify the adaptive increments obtained from the theoretical and laboratory studies, and to analyse how office users exercise adaptive opportunities in practice. Stochastic models of using AC, windows, desk fans and cool mats are also developed. Results show that the field study participants who exercise the given adaptive opportunities still find the environment thermally acceptable when the AC setpoint is 1°C higher.

Based on the studies in previous chapters, Chapter 7 proposes an MM system which incorporates an advanced window system, an associated heating, ventilation and air
conditioning (HVAC) system and a signalling system. This system encourages occupants to exercise adaptive behaviours and aims to limit the misuses of controls. Thirteen scenarios with different combinations of available adaptive behaviours, the availability of advanced window system and AC setpoints are proposed to show how this system contributes to energy conservation, comfort improvement and adaptive behaviours enhancement.
Chapter 2 - Literature Review

2.1 Thermal comfort models in relation to adaptations

Currently widely used thermal comfort models include steady-state models, such as the Fanger’s Predicted Mean Vote (PMV) model (Fanger, 1970) and the Standard Effective Temperature (SET*) model (Gagge et al., 1986), and adaptive comfort models, such as the one introduced by de Dear et al. (1997).

2.1.1 The Fanger’s PMV model

The PMV model developed by Fanger (1970) has been the most popular and referenced thermal comfort model for decades. The Fanger’s PMV model predicts thermal sensations based on six environmental and personal factors, namely air temperature, mean radiant temperature, Air speed, relative humidity, metabolic rate and clothing insulation. Predicted thermal sensations values range from cold (-3) to hot (+3) with zero representing thermal neutrality (Fanger, 1970). Fanger (1970) also developed a Predicted Percentage of Dissatisfied (PPD) model to predict dissatisfaction level based on PMV values. Brager and de Dear (1998) criticised the Fanger PMV model for treating occupants as ‘passive recipients of thermal stimuli’ as it was developed in the context of a climate chamber, whereas a real building environment with complicated and unpredictable thermal and non-thermal stimuli will drive occupants to adapt their behaviours and expectations to seek improved comfort consciously and unconsciously. A range of research results suggest that the Fanger PMV model is only valid in an AC building whose thermal environment is closely controlled, but fail to accurately represent occupants’ thermal sensation in NV or free-running buildings where occupants usually have more adaptive opportunities (de Dear and Brager, 2002; Humphreys and Nicol, 2002; Holopainen, 2012). However, by varying clothing level, metabolic rate and air speed used for PMV calculations (i.e. accounting for some aspects of behavioural adaptations), it can assess adaptive or, at least, partially adaptive processes (de Dear et al. 1997; Linden et al, 2008; Schweiker and Wagner, 2015). PMV values can be calculated by using the CBE Thermal Comfort Tool (Tyler et al., 2017)
2.1.2 SET*

The SET* model works to convert the six basic thermal stimuli (same as those used in the PMV model) to a single operative temperature (at RH 50%) at which persons with standardised metabolic rate and clothing will have the same skin wettedness and skin temperature (Gagge et al., 1986). The SET* model is capable of determine the increase in operative temperature that can be offset by exercising the adaptive behaviour in question and has already been used to estimate the offsets of operative temperature increase (or adaptive increments as christened Baker and Standeven (1996)) due to air speed elevation (ASHRAE, 2010; ISO 7730, 2005). Huang et al. (2014) are among those who experimentally verify the applicability of the SET* model in predicting the effects of air movements on occupants’ thermal sensation. SET* values can be calculated using the model developed by Professor Richard de Dear available at the website of The University of Sydney or the CBE Thermal Comfort Tool (Tyler et al., 2017).

2.1.3 Adaptive comfort models

An adaptive thermal comfort model (adaptive model for short) forms a linear relationship between outdoor temperatures and indoor thermal comfort temperatures (Brager and de Dear, 1998). It is widely recognised that occupants’ abilities to adapt their environment are powerful factors in determining thermal comfort (Baker and Standeven, 1996; de Dear and Cooper, 1997; Brager and de Dear, 1998; Fanger and Toftum, 2002; Haldi and Robinson, 2008). For this reason, adaptive models have experienced growing popularity, and have shown considerable capability in analysing thermal comfort in free-running buildings. However, adaptive models share a drawback that they insufficiently account for the effect of humidity and fail to capture the benefits of elevated air movement on one’s thermal sensation since the database used for the derivation of adaptive models include buildings with generally low indoor air speed (de Dear et al., 1997; Nicol and Humphreys, 2010; Candido et al., 2012; Vellei et al., 2017). They may also deal with clothing level and metabolic rate inflexibly, and therefore cannot provide some insight into the effects of individual adaptations (Fanger and Toftum, 2002). Hence, Fanger and Toftum (2002) questioned the capability of adaptive models to
predict the thermal comfort level of future occupants who may have new clothing styles and adjusted activity patterns.

2.2 Thermal Comfort adaptations

In terms of thermal comfort, adaptation may be defined as the process through which people enhance their perceptions of the surrounding environment. Before carrying on discussing three categories of adaptations, it is necessary to distinct thermal sensation from thermal comfort. Thermal sensation describes the detection of environmental stimuli, whereas thermal comfort builds on the thermal sensation and involves some psychological perception of the environment (de Dear, 2011). An example showing this distinction is that one might find it thermally comfortable in a hot environment. Adaptations can be divided into three categories, physiological (e.g. acclimatisation), psychological (e.g. change in expectation) and behavioural (e.g. the usage of windows, fans and clothing adjustment) adaptations. Many researchers argue that physiological adaptations play insignificant roles in one’s adaptation to a moderate environment (de Dear et al., 1997; Fanger and Toftum, 2002; Ugursal and Culp, 2012), whereas the remaining psychological and behavioural adaptations are perhaps the main means of improving one’s thermal comfort (de Dear et al., 1997). The following sections review physiological and psychological adaptations, whereas a detailed study of behavioural adaptations will be presented in Chapter 3.

2.2.1 Physiological adaptation

Physiological adaptations can be divided into genetic adaptation and acclimation (de Dear et al., 1997). The former looks at the progress of adaptations between generations, whereas the latter appears in one’s lifetime and is the interest of this study. Acclimation describes the reduced strain caused by the exposure to thermal stimuli as a result of the modifications of physiological reactions (de Dear et al., 1997). Typical physiological responses to heat include sweating and vasodilatation, which will be improved when acclimation takes place. It is widely accepted that a heat acclimated person will reduce metabolic rate and increase sweat volume with dropped salt concentration (Nielsen et al., 1993; Hori, 1995; Pandolf, 1998; Schweiker et
al., 2013), and Baker and Standeven (1996) and Cândido et al. (2012) also found that the change in core body temperature is also a result of acclimation. Apart from the physiological reactions, Auliciems and Szokolay (1997) suggest that acclimation also involves a psychological process which, along with physiological responses, adjusts the subject’s temperature preference towards the thermal stimuli. An example describing this shift in temperature preference may be that coastal residents in Australian have a lower temperature limit and can tolerate higher humidity than those living in the inland of Australian (Macfarlane, 1958).

Several experiments have been conducted in order to explore the effectiveness of acclimation as an adaptive process to improve one’s thermal sensation and acceptability. Based on experiments conducted in climate chambers, Cândido et al. (2012) showed that acclimated subjects with higher core body temperatures had improved thermal acceptability over hot environments. Schweiker et al. (2012) argue that most heat acclimate studies focused on long-term acclimation to hot environments or short-term acclimation to extreme conditions, such as the above experiment of Cândido et al. (2012), but few of these experiments analyses how an acclimated occupant perceives an environment with moderate temperature levels, such as office environments. The experiment of Bierley (1996) is an exception.

In the experiment of Bierley (1996), acclimated subjects (2h per day exposure to an environment 45°C and 40%RH for consecutive 4 days) do have evident acclimation response (increased sweat rate, higher tolerance of heat stress, etc.) but barely changes thermal sensation on a neutral (23°C, 70%RH, PMV=0) and warm (29°C, 50%RH, PMV=1.5) environments thermal conditions. Parsons (2002) recognised this result and claimed that heat acclimation has a limited effect on one’s thermal sensation range from neutral to warm. One may argue that a longer period than four days is required to reach a fully developed acclimation, but in terms of short-term acclimation in a moderate climate like Germany, 75% of the peak level of acclimation to heat would appear within 4-6 days, and the acclimation will disappear within 1-4 weeks after the removal of the heat exposure (Schweiker et al., 2012).
Consistent with the above analysis, many researchers believe that physiological acclimatization plays an ignorable role in one’s adaptation to a moderate environment (Brager and de Dear, 1998; Fanger and Tofume, 2002; Ugursal and Culp, 2012). The remaining psychological part of acclimation will be discussed further in Section 2.2.2.1.

2.2.2 Psychological adaptations

Occupants’ perceptions of environmental stimuli are influenced by psychological processes, which are dependent on occupants’ expectations, the state of mind, satisfaction level, etc. Nikolopoulou and Steemers (2003) regarded expectation, naturalness, environmental stimulation, perceived control, time of exposure and experience as the main psychological factors for an outdoor urban context. These may also be applicable to the indoor context but the roles they play could differ significantly from those when they are used in an indoor environment. Instead of using the above six factors, seven factors for indoor environment, all of which are frequently mentioned in literature, are discussed below. These seven factors are past thermal experience (psychological acclimation), naturalness and environmental stimulation, perceived control, perceived temperature, seasonal and diurnal effects, cognitive tolerance and contextual effects.

2.2.2.1 Past thermal experience (psychological acclimation)

The human body will become less sensitive to a thermal stimulus when repeatedly exposed to it, leading to the lessening of expectations (Glaser, 1966; Frisancho, 1981). Hence, past thermal experience may influence the expectations of the current thermal environment. Cândido et al. (2012) and Ugursal and Culp (2012) are among who experimentally verify the existence of this psychological acclimation.

2.2.2.2 Naturalness & environmental stimulation

Naturalness refers to the level of an environment free from artificiality (Griffiths et al., 1987). A higher level of naturalness may lower one’s expectation on the thermal environment, which can to some extent explain people have a higher tolerance of more extreme outdoor
conditions than indoor ones (Nikolopoulou and Steemers, 2003). A natural environment usually has many environmental stimuli (fresh air, daylight and natural wind), and enjoys the feature of variation (diversity), which may also play a key role in thermal expectations.

Nikolopoulou and Steemers (2003) emphasised the benefits of naturalness by comparing the actual thermal votes of outdoor persons with the results calculated by the PMV-PPD model, but studies have shown that the PMV-PPD model, designed for indoor environments, could not accurately calculate outdoor radiation flux (Höppe, 1997). In this sense, the Universal Thermal Climate Index (UTCI) model is more suitable for the comparison (Höppe, 2002). Moreover, Chun et al. (2004) argue that the PMV model is not able to reflect the personal and environmental features of an outdoor environment which could be highly asymmetric and unsteady. Despite that, strong evidence has confirmed the importance of naturalness & environmental stimulation on one’s thermal sensations.

Closely controlled environments would cause occupants to be sensitive to non-thermal stimuli, such as air quality, lighting, acoustics, etc., and this may be one of the main causes of sick building syndrome (SBS) (Baker and Standeven, 1997). It is also argued by Ouyang et al. (2006) Li et al. (2007) that natural wind differs considerably from mechanical wind in velocity fluctuation, and natural wind was found superior over mechanical wind on one’s thermal sensations at the same temperature and average velocity in a chamber experiment (Zhou et al., 2006). Moreover, Arens et al. (2006) argue that inhomogeneous environments could enhance one’s comfort sensation in the case that the whole body thermal stress is relieved by segments cooling/heating.

It is worth mentioning another plausible justification for the benefits of naturalness & environmental stimulation, the pleasure principle, which is proposed by de Dear (2009 and 2011). The pleasure principle is based on alliesthesia, which is a physiological phenomenon defined as the pleasure induced by external environmental stimuli that could restore a displaced variable within the milieu interieur (Cabanac, 1971). A simple example of alliesthesia
is that food brings pleasure to a hungry subject (positive alliesthesia), but unpleasant feelings to a full one (negative alliesthesia) (de Dear, 2009 and 2011). In terms of transient thermal environments, people would feel pleasant when environmental stimuli are working to drive skin or core temperature to the comfort set-points, although these set-points have not been reached. This theory may challenge currently widely recognised physiology-based thermal comfort models, ranging from the simple PMV model to multi-segment models, which determine thermal sensation by comparing thermal indicators (e.g. core and local skin temperatures and the rate of change of core and local skin temperatures) with certain setpoints. Cabanac (2006), Romanovsky (2007) and Kingma et al. (2012a) are among who questioned setpoints-based thermoregulation theories, and therefore to some extent support the pleasure principle. Instead of relying on setpoints-based thermoregulation theories, Kingma et al. (2012a) created a neurophysiology-based thermal sensation model in which thermal sensation is determined by information from core and skin warm thermoreceptors.

2.2.2.3 Perceived control

Perceived control is related to both available control and exercised control (Paciuk, 1989). The former denotes the knowledge of the number of available controls, whereas the latter means the acquaintance of the effectiveness of those available controls after manipulating them. People with high perceived control would attain comfort in a more efficient way, provided that controls work properly. Lacking perceived control, on the other hand, may lead to the sensation of stress (Baker and Standeven, 1996; Schweiker et al., 2013). Furthermore, Baker and Standeven, (1996) postulate that a lack of control opportunities limits one’s inherent adaptive ability, and in turn narrows one’s neutral comfort zone.

Nikolopoulou and Steemers (2003) presented an example to demonstrate the benefits of high perceived control: the predicted percentage of dissatisfactory (PPD) given by the Fanger PPD mode are compared with the actual percentage of dissatisfactory of people staying in an outdoor environment by their own choice and that of who are waiting for someone and the predicted percentage. It showed that the actual percentage of dissatisfactory of people
waiting for someone is in good agreement with predicted ones, while individuals who choose to stay in the place have much more positive thermal sensations than the predicted ones.

However, special attention should be paid to the distinguish the effects of perceived control from the effects of actual control actions, since it is very difficult to determine whether one’s enhancement in thermal sensation is attributed to psychologically perceived controls or to the improvements in physical environment as the result of control operations (Schweiker et al., 2012).

2.2.2.4 Perceived temperature

Rohles (1980) believe that the state of mind influences thermal sensation. Rohles and his colleges conduct a few experiments to back up this theory. One experiment is to evaluate thermal sensations of three groups of people (those who are not provided with temperature information against those who are informed with correct and incorrect temperature information), all of who are exposed to the same physical environments (20°C, 21°C, 22°C, 23°C) (Rohles and Kerulis, 1980). It was found that the ‘informed’ group consistently has warmer sensation than the ‘uninformed’ group, but the trend of how the ‘misinformed’ group react are less predictable. Nevertheless, how this cognitive effect may affect thermal sensation cannot be derived from this experiment.

Howell and Stramler (1981) also found a strong correlation between cognitive variables, in particularly perceived temperature, and thermal sensation from field studies. However, the results of another field study conducted by Schiller et al. (1988) opposed this finding.

2.2.2.5 Seasonal and diurnal effects

The time within a year and time of a day may also affect thermal sensations of a person upon a given environmental (Mishra and Ramgopal, 2013). For example, cool temperatures are more favourable than warm ones in summer but it is the other way round in winter (Humphreys, 1976; Rohles, 1980). However, literature did not strictly evaluate the weight of
physical and personal parameters (clothing level, metabolic rate, etc.) in this phenomenon and, additionally, it may be to some extent explained by the theory of past thermal experience.

### 2.2.2.6 Cognitive tolerance

Baker and Standeven (1996) suggest that people are more tolerant of stimuli, such as sunbeam and draught, if they have good knowledge of them. This tolerance can explain the phenomena that people will not be so stressful when temporarily exposed to an extreme outdoor environment and enjoy sun exposure in leisure time. Hence, it is reasonable to speculate that if occupants have a good knowledge of the indoor temperature variations, they would tolerate the temporarily emerged extreme temperatures. The thermal comfort standard, EN15251, allows a building’s thermal environment to deviate from the comfort zone for 3-5% of working hours, and therefore somehow recognises the existence of the cognitive tolerance.

### 2.2.2.7 Contextual effects

Contextual effects are related to one’s perception of the indoor environment. Distinct from naturalness & environmental stimulation mentioned above, contextual effects in the context have more to do with artificially environmental factors. Contextual effects can be regarded as a joined effect of a variety of indoor environmental stimuli, such as job pleasure, layout, decoration, lighting, glare, noise and cleanliness.

Rohles (1980) found people would feel colder in a commercial refrigerator-liked climate chamber than in the same climate chamber after it is embellished by installing carpet, covering walls with walnut panels, using visual friendly lamps, adding comfortable chairs and tables. This may be due to one’s experience that commercial refrigerator is cool whereas it is usually comfortable to stay in a well-embellished space, and it may indicate the working environment could psychologically influence thermal sensation. However, it is arguable that radiant temperature can be affected by the embellishment and one’s clothing level is added
due to the insulation provided by the comfortable chair, both of which directly related to one’s thermal sensation.

Oseland (1995) compared the comfort temperature of a same group of people in a climate chamber, their homes and offices with almost identical physical conditions. Results showed that the comfort temperature in the climate chamber is 2.2°C and 0.7°C higher than those in homes and offices, respectively. On contrary, Beizaee and Firth (2011) found a same group of people have 0.2°C lower comfort temperature in offices than that in homes. The contradictory results show that the effects of contextual effects on occupants’ thermal perceptions may be uncertain.

Although the benefits of overall contextual effects can be uncertain, it is highly likely that positive individual contextual factor is capable of contributing to one’s thermal comfort level. One good justification from field studies is that a room with well-decorated plants improves the thermal comfort level of occupants (Qin et al., 2014; Mangone et al., 2014).

2.3 Quantifying psychological adaptations
Above study has shown that physiological acclimatisation plays an ignorable role in one’s adaptation to a moderate environment and few existing literature looks at the quantification of physiological adaptations, so this section will focus on reviewing of the quantification of psychological adaptations (the quantification of behavioural adaptations will be discussed in Chapter 3). Nikolopoulou and Steemers (2003) claim that half of one’s thermal sensation can be attributed to psychological adaptations in terms of an outdoor urban context. However, this value is probably different in the context of the indoor environment. There are several studies attempting to quantify psychological adaptations or evaluate their relative significance compared to behaviour and physiological adaptations. Some typical ones are discussed in the following paragraphs.
2.3.1 Analysis in de Dear et al. (1997)

De Dear et al. (1997) evaluated the relative significance of physiological adaptations compared to behaviour adaptations by comparing the discrepancies in neutral temperatures calculated by the PMV model and those derived from the adaptive model. They treated the PMV model as a partially adaptive model by coupling it with two linear equations describing how outdoor temperatures correlate to clothing level and indoor air speeds. These two correlations were derived from the same database used for the original adaptive model adopted by ASHRAE (2010) and found to be statistically significant. In fact, a correlation between outdoor temperature and metabolic rate was also drafted but it turned out to be statistically insignificant and therefore was discarded.

By plotting the neutral temperatures calculated by the partially adaptive PMV model against outdoor temperatures, a similar line as the adaptive model was obtained, as shown in Figure 2.1. Since the gradient of the partially adaptive line is about half of that of the adaptive model, De Dear et al. (1997) claim that the other half should be attributed to psychological adaptations. However, this study overlooked other commonly exercised adaptive behaviours, such as posture adjustments and having a cold drink. Wyon and Holmberg (1972) and Raja and Nicol (1997) suggested that total body surface area varies due to posture adjustments which were found to be strongly correlated to indoor temperatures and therefore to some extent associated with outdoor temperatures. In the study of Haldi and Robinson (2011), a correlation between cold drink taking and outdoor running mean temperature was found. Hence, it is reasonable to argue that psychological adaptations would play a less important role than what was suggested by De Dear et al. (1997).
Figure 2.1. Comparison of comfort temperatures given by the original adaptive model in ASHRAE (2010) and those by the partially adaptive PMV model (De Dear et al., 1997).

2.3.2 Analysis in Fanger and Toftum (2002)

As discussed above, Fanger and Toftum (2002) proposed empirical expectancy factors to represent psychological adaptations in non-air-conditioned buildings. Several studies have incorporated the expectancy factors into the analysis of occupants’ thermal comfort in naturally ventilated buildings. Ji et al. (2006), Zhang et al. (2010), Rajasekar and Ramachandraiah (2010 and 2011) and d’Ambrosio Alfano et al. (2013) are among who claim that the corrected PMV results by using expectancy factors are in high degree agreements with actual thermal sensation votes (TSVs). However, others, including Wong and Khoo (2003), Tablada et al. (2005), Zhang et al. (2007) and Nguyen et al. (2012), argue that the corrected PMV model fail to correspond with actual TSVs, in particular at low TSVs. The large discrepancies between corrected PMV results and actual TSVs at low TSVs are also found in the studies of those who demonstrate the success of expectancy factors. This phenomenon would be understandable if looking at the working principle of expectancy factors. Expectancy factors multiplied by originally PMVs to obtain corrected PMVs, so, in terms of the change in magnitudes, higher PMVs are adjusted more significantly compared with lower PMVs and the predicted neutral point (PMV=0) would remain constant. Hence, expectancy factors just reflect that the lower expectation could increase one’s tolerance for extreme condition, but
disregard the fact it may also cause a shift in one’s neutral temperature. In this sense, the reliability of the method of expectancy factors needs further justifications.

2.3.3 Analysis in Nguyen et al. (2012)

As an extreme case, Nguyen et al. (2012) found similar neutral SET*s in NV and AC building located in South-East Asia with a hot humid climate, indicating behaviour adaptations overwhelm the other two adaptive processes. However, the SET* model takes account of the effects of relative humidity which is usually higher in NV ventilated buildings than in AC buildings. Hence, it is possible that the benefits of psychological adaptations counterbalance the negative effects caused by the high relative humidity. This speculation, however, is inconsistent with the findings of (Givoni et al., 2004) and (Givoni et al., 2005) that people in Thailand and Hong Kong have acclimatised to the humid climate so that are not so sensitive to humidity as what is suggested by various comfort indices. Anyway, the study of Nguyen et al. (2012) implies that the effects of psychological adaptations are not as significant as those suggested by the above two studies, or, at least, with regard to some specific cases.

2.3.4 Analysis in Zhou et al. (2014)

Zhou et al. (2014) aimed to experimentally quantify the effect of anticipated control on occupants’ thermal comfort and thermal sensation. The experiments were conducted in a climate chamber which provides controls of an electric heater, a vapour humidifier and a cooling coil. Results show that anticipated control would lead to a reduction of 0.4-0.5 in one’s thermal sensation vote and an increase of 0.3-0.4 in one’s thermal comfort vote. However, during the experiments, air temperatures rise 1°C per minute from 26°C to 35°C. Such a rapidly increasing rate is not common in an actual indoor environment, and the effects of experimental subjects’ past thermal experiences do not seem to be negligible. Hence, the relative weights of past thermal experience and perceived control on the increase in thermal comfort and sensation are rather vague. Fanger and Toftum (2002) argue that occupants’ perceived control in naturally ventilated buildings may not be higher than that in air conditioning buildings with well-located thermostatic control, so the effect of perceived
control on thermal comfort improvement in naturally ventilated buildings is unlikely to be more significant than that obtained by this study.

2.3.5 Influence of psychological adaptation

Above studies demonstrate that it is rather difficult to give a proper quantitative influence of psychological adaptations, but it seems that their influences are less significant than what indicated in previous studies. The weight that psychological adaptations account for one’s thermal sensation for the context of an indoor environment is highly likely less than 50% as suggested by Nikolopoulou and Steemers (2003), since indoor environment usually has lower levels of control opportunities, which affects one’s perceived control and naturalness & environmental stimulation, than those of the outdoor environment. Moreover, due to the complexity of the components of psychological adaptations, their effects could vary significantly from site to site.

There are seven categories of psychological adaptation analysed in detail, and among them, only psychological acclimation, naturalness and environmental stimulation, perceived control, contextual effects have demonstrated clear evidence to influence one’s thermal sensation. It is of interest to evaluate the interrelationships between different categories, which will pave the way for more detailed studies on psychological adaptations in the future.

A speculative network is depicted, as shown in Figure 2.2, similar to that for outdoor psychological adaptations in the work of Nikolopoulou and Steemers (2003). Arrow lines denote the interrelationships between two categories. The interrelationships can be either one-way or two-way but are not weight related. In the context of the indoor environment, naturalness & environmental stimulation and contextual effects are highly interconnected with each other, and they are two major non-thermal influences. The past thermal experience, on the other hand, reflects the thermal influences from both the indoor and outdoor environment. It is postulated that occupants evaluate their non-thermal factors in parallel with analysing thermal factors. Perceived control is mainly related to available controls, both
personal controls (e.g. activity adjustment) and environmental controls (e.g. window operation) and therefore is interrelated with environmentally psychological factors and personal ones (i.e. cognitive tolerance). It is worth noting that cognitive tolerance is very sensitive to all other categories.

Although psychological adaptations may not be easily quantifiable, they can be deliberately orientated to have positive impacts. Spaces can be designed and decorated to embrace natural environment, to provide pleasant visual, auditory and spiritual experiences, and to allow abundant control opportunities. In that case, highly positive psychological adaptations can be achieved.

![Figure 2.2. Interrelationships between categories of psychological adaptations.](image)

**2.4 Stochastic behaviour models**

Building performance simulation has been increasingly adopted at the design stage of an architectural project, owing to its exceptional capability of allowing the design team to compare and contrast between different design options and, eventually, improving the project (Wong et al., 2000; Clarke, 2001; Goldstein et al., 2010). However, various Post-Occupancy Evaluations (POEs) showed that there was a considerable gap between simulated and actual performances, and suggested that this discrepancy was predominantly caused by the unsuccessful modelling of occupant behaviour (Karlsson et al., 2007; Egan, 2009; Demanuele et al., 2010; Dall’O’ et al., 2012; Menezes et al., 2012).
The most commonly used method of representing occupant behaviour relies on the diversity profile (i.e. occupancy patterns or system loads over time), which has a major drawback that it may not reflect the stochastic characteristics of occupant behaviour (Bourgeois, 2005; Page, 2007; Tabak, 2009). To address this issue, there is a growing interest in the sub-hourly analysis of occupants’ stochastic behaviours based on field studies and mathematic modelling. This has led to the emergence of some advanced stochastic behaviour models and, in turn, more realistic simulation of building performance. An important point to note is that stochastic behaviour models may not have distinct advantages over detailed diversity profiles in whole building energy simulation (Parys et al., 2011b), but show a great potential in effectively determining the robustness of a design solution to occupant behaviour (Hoes et al., 2009; Parys et al., 2010; Hoes et al., 2011). The robustness of a design solution to occupant behaviour can be defined as the capability of the design solution to maintain desired performance under the effect of various uncertain occupant behaviours (Leyten and Kurvers, 2006; Hoes et al., 2009).

Generally, user behaviour in an office building can be split into two aspects. One describes occupancy, namely the distribution and movements of occupants, whilst the other concerns users’ control of building components, equipment and services systems (Hoes et al., 2009; Wang et al., 2011).

### 2.4.1 Diversity profile

The diversity profile is widely used to reflect occupancy and how occupants control equipment and services systems. The fundamental element of diversity profile is the diversity factor, which a value ranging from zero to one, describing occupancy level and the load level of equipment and services systems (a value of zero denotes no occupancy/load and a value of one represents full occupancy/load). Daily occupancy/load variations are usually indicated by assigning a set of 24 hourly based diversity factors which can be different from one day type to another (day types include weekdays, weekends and holidays). Typical diversity profiles (two examples shown given in Figure 2.3&2.4) can be found in some energy standards and
codes (MNECB, 1997; ASHRAE 90.1, 2001), and the database of various simulation software programmes (EE4, 2000; DeST, 2008; EnergyPlus, 2009).

However, these diversity profiles are virtually independent of building design factors, so simulations based on them could hardly represent actual situations. Abushakra et al. (2001) and Davis and Nutter (2010) derived more realistic diversity profiles by considering building design details based on field studies. Even so, this approach cannot overcome the inherent shortcomings of diversity profiles that they could barely be linked to environmental conditions and scarcely reflect the stochastic characteristics of occupants (Bourgeois, 2005; Wang et al.,
25

2011). Such limitations may be exceptionally sensitive in buildings with abundant occupant control opportunities (Bourgeois, 2005).

**2.4.2 Stochastic behaviour models**

Stochastic behaviour modelling is on the basis of the observations on how occupants behave in real cases under the effects of various stimuli. A stochastic model demonstrates a relationship between those selected stimuli (input variables) and an action (output variable) by formulating an algorithm. Due to the variation of occupant behaviour amongst different analysed buildings and the compromise between comprehensiveness and applicability, various models may adopt different stimuli and algorithms though they intend to predict the same action. The statistical and mathematic concepts of formulating algorithms can be found in the work of Haldi (2010) and Parys et al. (2011a).

Apart from the stochastic characteristic of occupant behaviour, individuals’ diversity is another important factor that leads to uncertainty of building energy performance. The studies of Hoes et al. (2009), Parys et al. (2011a) and Haldi and Robinson (2011) relied on different methods to reveal individuals’ diversity. Hoes et al. (2009) purely defined extreme users (all passive or active users for the control of the building), whereas Parys et al. (2011a) defined certain ranges of the percentages of passive and active users. Haldi and Robinson (2011) used a much more explicit method that every occupant was assigned with a probability function based on data collected from field studies.

**2.4.2.1 Models for occupancy**

Mocdonald and Strachan (2001) propose a stochastic model based on Monte Carlo Analysis, a sensitivity analysis method. This model arbitrarily selects input values, all of which are normally distributed values, so values around the modal value are more likely to be chosen than extreme values (Lomas and Eppel, 1992). These randomly selected values are then simulated repeatedly to obtain an overall uncertainty (Lomas and Eppel, 1992). Wang et al. (2011) criticise this model that it neglects the space and time dependent properties of
occupancy.

Wang et al. (2005) proposed a probabilistic model on the basis of the ‘Poisson’ process, demonstrating that vacancy intervals follow the exponential distribution. Moreover, Page et al. (2008), focusing on a certain zone of a building, used the inhomogeneous ‘Markov chain’ approach to model the probabilistic presence of occupants. The above two methods take account of the time-dependent feature of occupancy and may be successful in occupancy modelling for a single office/zone, but is not capable of realistically reflecting the movements of occupants between zones.

More recent models began to consider the zone-to-zone movements of occupants. Built on the Markov chain property of the model of Page et al. (2008), Liao et al. (2011) introduced a model that treats each occupant as an agent. This model has been verified to have capability in simulating the scenario of occupants in a single zone, but its capability of dealing with a building with multiple zones has still not yet been well validated since there is a lack of reliable fieldwork data that can be used for validation and correction. Free from the constraint of occupant and zone numbers, a model developed by Wang et al. (2011) relies on the homogeneous Markov chain, based on the concept that occupant movement is subject to ‘Markovian’ property, to predict the location of each occupant and thus determining the occupancy level.

A more comprehensive approach to simulating occupancy may be detailing occupant activities. Goldstein et al. (2010) put forward a schedule-calibrated occupant model which considers frequency, priority, duration, etc. to predict a detailed sequence of probable activities. Models with similar functions are the model called ‘User Simulation of Space Utilisation’ (USSU) developed by Tabak (2009) and the model derived by Zimmermann (2007). These models are based on enormous surveys on realistic activities and specific mathematical techniques and could represent the stochastic occupancy in a more reliable way. However, they may be fairly building specific and therefore less practical in general use, as argued by Parys et al. (2011a).
2.4.2.2 Models for artificial lighting control

An early ‘Lightswitch’ model developed by Newsham et al. (1995) associates the sophisticated estimation of individual’s arrival, departure and temporary absence with the light switching motions at 5-minute steps, resulting in detailed lighting diversity profiles at an average level. Although lowering time steps in diversity profiles contributes to the accuracy, it is still less reliable than stochastic models as mentioned in Section 2.1.

Reinhart (2004) developed the ‘Lightswitch-2002’ algorithm to model occupants’ stochastic controls of artificial lights. The algorithm, based on field evidence (Reinhart, 2001) and surveys (Reinhart and Voss, 2003), links various switching patterns to user occupancy profiles and work plane illuminances data. One of the key features of the algorithm is that it follows the concept of passive and active users (Love 1998). Passive users switch lights independent from indoor daylight level, whereas active users activate the artificial lighting system merely when the zone is not sufficiently daylit. Other key features include that it considers the stochastic characteristic of control motions and the dynamic picture of both environment and occupants at 5-minute steps.

However, due to the fact that the estimate on occupancy is too simple; lack of statistics about the percentage of active/passive users; inherent difficulties in taking account of the locations of switches etc., more quantitative field studies need to be conducted to improve the algorithm. Detailed data from a field study of the probability of intermediate light switching, prepared by Lindelof and Morel (2006), may be adopted. Alternatively, it may be coupled with external and more realistic models as suggested by Bourgeois (2005), and its coupling with the USSU occupancy model was put forward by Hoes et al. (2009).

2.4.2.3 Models for shading devices control

Parys et al. (2011a) state that the first comprehensive model for predicting occupant control of shading device is the blinds section in the Lightswitch-2002 model, but it describes fairly simple blind usage (only fully open or closed are defined) and fails to reflect the stochastic
Inkarojrit (2005) developed a stochastic algorithm with the form of a logistic probability distribution, on the basis of a field study conducted in two air-conditioned buildings. Major driving variables defined in the model are the mean and maximum luminance of the window, vertical solar radiation and occupant sensitivity to glare. The probable drawbacks of this model are that it can only reflect the actions at arrival and it is challenging to define a standard occupant sensitivity to glare.

The model of Haldi and Robinson (2010), based on a Markov chain and logit analysis, incorporates much more detailed occupancy scenarios, and is the most cutting-edge stochastic model for predicting blind operation as argued by Parys et al. (2011a). However, the effect of temperature is not considered and needs to be further validated in other office buildings.

2.4.2.4 Models for window operation

Fritsch et al. (1990) derived a stochastic model regarding the use of windows for the purpose of ventilation based on a field investigation of four offices in Lausanne, Switzerland. The model adopts Markov chains to relate time-dependant window angle to preceding window angle and external temperature. One of the limitations of this model is that it may only be applied in heating seasons in which the field study was carried out. The whole-year window use behaviours may be analysed by using the model, which basically expresses the motion of opening window as a function of external temperature, prepared by Nicol and Humphreys (2004).

A model developed by Herkel et al. (2008), based on a field study in Germany, shows that the degree of window open is not only dependent on the external temperature and the time of a day, but also occupancy features. As more research interest has been placed on naturally ventilated buildings, window operation behaviours are found to be strongly correlated to the indoor temperature which has been treated as an essential parameter in recently developed stochastic models (Rijal et al., 2007; Haldi and Robinson, 2009; Yun et al., 2009).
To more realistically predict the window operation probability, the stochastic model derived by Page (2007) takes account of indoor air quality and the model of Haldi and Robinson (2009) even considers the occurrence of rain. Similar to the concepts of passive and active users introduced by Love (1998), the model of Yun et al. (2009) divide occupants into active, medium and passive users who are assigned with different probabilities of opening windows at arrival, and Yun and Steemers (2010) improved this model to be valid in buildings where night ventilation takes place. Additionally, the adaptive principle of occupants is paid attention to, to some extent, in the models developed by Rijal et al. (2007), Herkel et al. (2008), Yun and Steemers (2008) and Haldi and Robinson (2009).

2.4.3 Coupling stochastic behaviour models with whole building simulation programmes and their applications in building performance simulations

Theoretically, any algorithm-based stochastic behaviour models can be integrated into any building simulation programme, provided that the source codes are available. Some building simulation programmes, such as ESP-r, CitySim and SUNtool, have already incorporated a few stochastic algorithms, whereas other programmes, such as TRNSYS and EnergyPlus, are capable of linking to external code writing environments, and therefore can also integrate stochastic behaviour models. Table 2.1 summaries of these applications.

2.4.3.1 ESP-r

The whole building simulation programme, ESP-r, has integrated a user behaviour module, the Sub-Hourly Occupancy Control (SHOCC) developed by Bourgeois (2005), which is mainly built on the Lightswitch-2002 model to predict occupancy and the occupant control of artificial lighting and shading devices. As its occupancy modelling is too simple, Hoes et al. (2009) put forward the coupling with the USSU occupancy model. The models of Rijal et al. (2007) and Yun et al. (2009) have also been incorporated into ESP-r for simulating window operation. Two case studies conducted by Bourgeois et al. (2006) and Hoes et al. (2009) are introduced below.
Bourgeois et al. (2006) coupled the SHOCC and ESP-r to investigate the energy demand of single-zone offices in three scenarios:

(1) Lights are on continuously and blinds are under no control (equivalent to all passive occupants scenario).

(2) Active manual control of lights and blinds (equivalent to all active occupants scenario).

(3) Active manual control of lights and blinds, together with advanced dimming and occupant-sensing systems (equivalent to all active occupants and advanced lighting system scenario)

Two offices in Rome and Quebec respectively are studied. In both cases, the second scenario shows a significant reduction in the total primary energy demand in comparison to the first scenario, and the third scenario further reduces the demand slightly. The results (shown in Figure 2.5 and Figure 2.6) are given in absolute values arising from the extreme scenarios, without considering the distribution of passive and active users.

Figure 2.5. Annual primary energy requirements for heating, cooling and lighting in Rome.
Hoes et al. (2009) combined the USSU occupancy model with the SHOCC in the ESP-r simulation of the energy demand of an office with five types of envelope design as shown in Figure 2.7.

The robustness of these designs to occupant behaviour was reflected from the variations in heating/cooling and primary energy demand arising from twenty-four office user types, which were defined by combining three aspects of user characteristics as follows:
(1) Constant or irregular occupancy level.

(2) Passive or active users of blinds and/or lighting.

(3) Low, medium or high levels of internal heating loads (internal heating loads arising from equipment, etc. is regarded as a parameter relevant to occupant behaviour in this study).

(Note: Characteristic 1, 2 and 3 have 2 options, 4 options and 3 options respectively, so there are a total of twenty-four \((2\times4\times3)\) combination ways.)

The results, presented in Figure 2.8, illustrates that the scenario of low thermal mass and large opening shows the best robustness to user behaviour, but this kind of design may not be feasible as it would lead to an extremely uncomfortable indoor environment (i.e. very high indoor temperature). Hence, it is important to combine the robustness design and thermal comfort considerations to come up with an overall robust solution.

![Relative standard deviation per performance indicator](image)

**Figure 2.8.** Relative standard deviation (RSD) of several performance indicators for the five design solutions. The RSD is calculated from the average value and standard deviation of a performance indicator. The smaller the RSD is, the more robust the corresponding design solution to the user behaviour (Hoes et al., 2009).
2.4.3.2 TRNSYS and MATLAB

In the study of Parys et al. (2011a), the model of Lightswich-2002 model for occupancy and artificial lighting control, the model of Haldi and Robinson (2009) for window control and the model of Haldi and Robinson (2010) for shading device control were coded in MATLAB and integrated in TRNSYS (MATLAB is an environment for numerical computing and data visualisation, and a language for algorithm derivation and programming (Mathworks, 2012); TRNSYS is a modelling tool primarily for energy systems and capable of conducting whole building energy simulation (TRNSYS, 2012)). Using the tool and the integrated behaviour models, Parys et al. (2011a) analysed the energy demand of an office building and its uncertainty arising from different defined percentages of active and passive users through Monte Carlo analysis. The results (shown in Figure 2.9) of the uncertainty analysis is relatively modest compared with the above studies carried out in single zone scenarios.

Figure 2.9. Results of the uncertainty analysis (a) Lighting energy use frequencies for
December. (b) The average value and standard deviation of monthly heating demand. (c) The average value and standard deviation of monthly cooling demand. (d) The average value and standard deviation of monthly lighting energy use (Parys et al., 2011a).

In addition to the building simulation tools described above, SUNtool and EnergyPlus are also capable of integrating stochastic models, but their applications in office energy simulation are not available.

2.4.3.3 CitySim
Haldi and Robinson (2011) introduced the integration of the aforementioned model of Haldi and Robinson (2009) for window control and the model of Haldi and Robinson (2010) for shading device control into CitySim, which is an urban energy simulation programme capable of simulating building-related energy performance. In the study, the energy demand simulation of a single-zone office was conducted by considering different designs of window operable ratio, insulation thickness and heating and cooling setpoints. Instead of designing ‘average users’ in the above case studies, this study characterises behaviour diversity using calibration parameters derived from numerous individuals. The results indicate that the worst-case occupant behaviours doubled the energy demand of the office in comparison to the optimal occupant behaviours, and the inter-individual variability on energy demands has a more significant impact than that of building design variables, on the basis of relatively distant heating and cooling setpoints.

2.4.3.4 SUNtool
Page (2007) developed an occupancy model (the same as the aforementioned model of Page et al. (2008), the aforementioned window operation model and a model of appliance control. These models, together with the Lightswitch-2002 model, were imported into the SUNtool, a simulation tool for the urban-scale energy modelling. This tool was only applied in simulating a domestic building, so the application would not be discussed in this essay.
2.4.3.5 EnergyPlus and Building Controls Virtual Test Bed (BCVTB)

EnergyPlus is an advanced whole building simulation programme and the ‘Building Controls Virtual Test Bed’ (BCVTB) provides a platform for coupling difference simulation programmes. BCVTB has already developed MATLAB and EnergyPlus interfaces, which means stochastic models can be coded in MATLAB and coupled with EnergyPlus.

Table 2.1. Summaries of four cases studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>Building simulation tool used</th>
<th>Applied stochastic behaviour models</th>
<th>Object of study</th>
<th>Robustness test /uncertainty analysis methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bourgeois et al. (2006)</td>
<td>ESP-r</td>
<td>Lightswitch-2002.</td>
<td>Two single-zone offices in Rome and Quebec respectively</td>
<td>Defining three lighting usage scenarios</td>
</tr>
<tr>
<td>Hoes et al. (2009)</td>
<td>ESP-r</td>
<td>The USSU occupancy model; Lightswitch-2002.</td>
<td>An office with five types of envelope design</td>
<td>Defining twenty-four office user types to test the robustness of five envelope designs</td>
</tr>
<tr>
<td>Parys et al. (2011a)</td>
<td>TRNSYS with MATLAB</td>
<td>Lightswitch-2002; the model of Haldi and Robinson (2009); the model of Haldi and Robinson (2010).</td>
<td>A whole office building</td>
<td>Defining four distributions of active and passive users.</td>
</tr>
<tr>
<td>Haldi and Robinson (2011)</td>
<td>CitySim</td>
<td>The model of Haldi and Robinson (2009); the model of Haldi and Robinson (2010).</td>
<td>A single-zone office</td>
<td>Characterising behaviour diversity using calibration parameters derived from numerous individuals</td>
</tr>
</tbody>
</table>
2.4.4 Discussions on the applications of the integrated stochastic models in building energy simulations

The applications were conducted using different stochastic behaviour models or building simulation programmes. Among them, only Hoes et al. (2009) and Haldi and Robinson (2011) also conducted robustness analysis of various design solutions. In terms of building/room energy simulations, only Parys et al. (2011a) analysed a whole office building whereas all others focused on a single zone. The variation of energy demands in Parys et al.’s study is considerably less significant than those in others’ studies and this may be mainly because extreme scenarios are not included in Parys et al.’s study. Other possible reasons include that the whole building aggregates diversely performing individual rooms and thus evening out the differences, and the whole building has limited behaviour opportunity whereas the individual room studies seem to have more adaptive potential. For these reasons, stochastic behaviour models may not be indispensable in determining yearly energy demand of a whole building or, at least, a building with little occupant control opportunities and deep plan. This may be quantitatively supported by the study conducted by Parys et al. (2011b) in which the replacement of the stochastic behaviours models with detailed diversity profiles results in an error of only about 5%.

With regard to the robustness analysis, they would be improved by introducing more design variables, such as orientation and glazing type (although this may result in significantly heavier computational load). Additionally, they should rely on some more detailed performance indicators since yearly heating/cooling demand or primary energy demand seems to be too generic. This could include comfort parameters related to light, heat or sound, as well as more qualitative aspects of access to control or views.

2.4.5 Issues of current stochastic behaviour models

Firstly, an issue associated with current stochastic behaviour models may be lack of validation of these models (Parys et al., 2011a). This leads to contradictory information in relation to choosing appropriate behaviour models that advanced stochastic models are comprehensive
but may be building specific as they are derived from detailed field studies and, on the other hand, some generic stochastic models show better practicality but are less successful in realistically reflecting the features of user behaviour. The study of Dong and Lam (2011) introduces an approach of verifying stochastic models for occupancy prediction, which relies on the sensor collected data of lights use, CO₂ concentration and noise levels and video camera observations to train algorithms for occupancy modelling.

Secondly, each existing stochastic model merely takes account of a limited number of stimuli, most of which are subject to physical environment-related incentives. Other stimuli, such as privacy concerns, are not well integrated into these models. Moreover, occupants’ adaptive behaviours, such as having drinks and changing clothes, have not been paid much attention to, not to mention the psychological adaptations of occupants.

Thirdly, it is important to develop stochastic models for the control of appliance and thermal environment control, and there is a need for more comprehensive stochastic modelling of occupancy, artificial lighting control, shading device control and window operation. Additionally, as most current models mainly focus on offices, there is a need to take account of other zone types in an office building, such as meeting rooms and cafeterias. The ultimate models should have flexible and comprehensive settings (based on a large database) that can be adjusted in accordance to specific functions and design features of a zone or building, and therefore are applicable to a wider range of scenarios.

Finally, in terms of practical use of the stochastic behaviour models, it is too complicated, and therefore unlikely, to rely on external languages for algorithm derivation. Hence, it needs more efforts to embed these models into some whole building simulation programmes. In this regard, the programmes, ESP-r, SUNtool and CitySim, are a step forward but they may need to continue to keep pace with the latest developments of behaviour models.
2.5 Mixed mode (MM) system

An MM system has three types, namely concurrent, changeover and zoned (Brager et al., 2007). A concurrent MM system allows occupants to freely operate windows and the associated HVAC system operates to meet air quality or thermal comfort requirements regardless of the status of the manually controlled windows (Brager et al., 2007). A changeover MM system, on the other hand, prevents the simultaneous usage of NV and the associated HVAC system and once manually or automatically controlled windows are opened, the HVAC system will be shut down (Brager et al., 2007). A zoned MM system is applied in a multi-zone space where some of its zones solely rely on NV and others are conditioned by an HVAC system (Brager et al., 2007).

2.5.1 Associated NV systems

NV is basically produced by naturally occurring pressure differences resulting from wind and/or internal heat sources (de Dear and Brager, 1998; Linden, 1999). Designing an NV system is a complicated task, requiring thorough considerations of a range of factors, such as occupant thermal comfort, building geometry, surrounding environment and climate. Although an NV system may not be capable of maintaining the indoor temperature within a narrow spectrum as an HVAC system is, this does not necessarily indicate occupants in NV buildings would feel less thermally comfortable than those in mechanically conditioned buildings. (de Dear and Brager, 1998; Gossauer and Wagner, 2007; Manchanda, 2008). This is due to the fact that people are active recipients of thermal stimuli, and therefore they would behaviourally, physiologically and/or psychologically adapt to their environment (de Dear and Brager, 1998). The effectiveness of NV systems can be enhanced by some advanced natural ventilation components, such as solar chimney (Carboun, 2013), atrium (Short and Lomas, 2007), double skin façade (Gratia and de Herde, 2004), earth ducts (BSRIA, 2008; Sustainable Building Construction, 2016) and underfloor air distribution (Deng et al., 2017).

2.5.2 Associated HVAC systems

Variable refrigerant flow (VRF), variable air volume (VAV) and fan-coil plus fresh air (FPFA) are
three commonly used centralised AC systems in China (Zhou et al., 2007). Among them, the VRF system is found to be superior to the other two systems in terms of energy performance (Zhou et al., 2007). More studies have been done to evaluate the energy performances of the VRF and VAV systems and claim the former is more energy efficient (Aynur et al., 2009; Kim et al., 2017; Lee et al., 2018).

One downside of the VRF system, as a refrigerant-driven system, is not capable of providing fresh air on its own. Hence, the VRF system has to integrate a separate mechanical ventilation (MV) system if indoor air quality is a big concern to the building users. The additional MV system can be in the form of dedicated outdoor air system (Park et al., 2017), heat pump desiccant system (Aynur et al., 2010), outdoor air processing unit system (Lee et al., 2017), etc. All the systems have the capabilities of dehumidifying and precooling/preheating the outdoor fresh air before delivering it into target rooms. The VRF system and the associated MV system work independently and therefore can efficiently control both indoor temperature and air quality. On the other hand, it is very challenging for an all-air system, such as the VAV system, to balance the requirements of thermal comfort and indoor air quality in an energy efficient way. For instance, if there is only fresh air requirement, the supply air at a low constant temperature (typically 13°C in a traditional VAV system) will be reheated to the room temperature, causing a large amount of energy waste. This is consistent with the argument of Aynur et al. (2009) that a VAV AC system with reheater may cause high energy penalty. However, the VAV system has the advantage of coupling a cooling system and an MV system, which leads to a relatively lower initial cost (Kim et al., 2017).

2.5.3 Thermal comfort evaluation in MM buildings

The widely used thermal comfort models mentioned above are normally used for evaluating thermal comfort of mechanically or naturally ventilated spaces, and there is no model specifically designed for MM spaces (Deng et al., 2017). Some researchers, such as Song and Kato (2004), May-Ostendorp et al. (2011) and Homod and Sahari (2013), applied steady-state models to evaluate thermal comfort in MM spaces. Short and Lomas (2007) and Ezzeldin and
Rees (2013) are among who adopted adaptive models for the thermal comfort evaluation. Luo et al. (2015), Deuble and de Dear (2012) and de dear and Brager (1998) conducted feasibility analyses of both steady-state and adaptive models and concluded that adaptive models would generally have better performances.

2.6 passive energy-saving strategies

2.6.1 Window signalling system

A window signalling system provides an energy efficient way to instruct occupants to operate windows properly (Ackerly and Brager, 2013). It uses lights or lighted signs to inform occupants of the environmental conditions and suggest window opening/closing actions (Ackerly and Brager, 2013). Some examples of the system’s interfaces are shown in Figure 2.10.

The logic behind the signalling system should be case sensitive and therefore it requires detailed surveys on the buildings before installing the systems (Ackerly and Brager, 2013). In order to make occupants more positively respond to the signals, it is necessary to make the system’s interface visible to occupants and ensure that users understand the logic behind the system (Ackerly and Brager, 2013).

![Figure 2.10. Types of signalling systems’ interface (Ackerly and Brager, 2013)](image-url)
2.6.2 Night ventilation

Night ventilation takes advantage of outside cool air during nighttime to cool down the structure of a building (Pfafferott et al., 2003; Finn et al., 2007; Artmann et al., 2008; Ramponi et al., 2014; Solgi et al., 2018). Factors affecting the effectiveness of night ventilation include heat gains, heat transfer coefficients, thermal mass (weight of building structure), air change rates and climate (Wang et al., 2009; Solgi et al., 2018). Both solar gains and internal heat gains are found influential to the efficiency of night ventilation (Kolokotroni and Aronis, 1999; Pfafferott et al., 2003). Artmann et al. (2008) is one of the few researchers taking into consideration heat transfer coefficients. Night ventilation has been proved to be very effective for heavy-weighted building (Finn et al., 2007; Artmann et al., 2008; Ramponi et al., 2014), and other researches also show that it is also helpful for light-weighted buildings or light-weighted buildings installed with phase change materials (Wang et al., 2009; Seong, Y. B. and Lim, 2013; Solgi et al., 2016). Air change rate is considered closely related to the efficiency of night ventilation in many researches (Blondeau et al., 1997; Shaviv et al., 2001; Pfafferott et al., 2003; Artmann et al., 2008; Wang et al., 2009). Moveover, Solgi et al. (2018) argue that night ventilation could be suitable for most climates.

Night ventilation can be divided into natural or mechanical night ventilation in terms of ventilation means. The former mainly relies on opened windows to achieve air exchange (Wang and Sun, 2006; Zhou et al., 2008), whereas the latter requires the assist of a mechanical ventilation to attain a controlled air exchange rate (Solgi et al., 2018). Other passive design strategies, such as windcatchers (Jomehzadeh et al., 2017), atriums (Eicker et al., 2006; Wagner et al., 2007), solar chimneys (AboulNaga and Abdrabboh, 2000) and double skin façade (Torres et al., 2007), can be used to enhance the performance of night ventilation

2.7 Developments on the existing static thermal comfort models

It has been commonly agreed that the PMV model may be misleading when applied in certain
cases, probably due to individual differences (within a building, among different buildings or different regions), measurement errors and the equation’s inherent limitations. As the PMV model is still one of the most recognised and popular thermal comfort models, many efforts have been taken to develop it by taking in consideration adaptive features. Three improvements on the PMV model are introduced in the following sections.

2.7.1 Adding expectancy factors
Fanger and Toftum (2002) recognised the fact that people in naturally ventilated buildings have different expectation for thermal comfort and modified the PMV model by introducing empirical expectancy factors. An expectance factor (ranging from 0.5 to 1) is multiplied by PMV to obtain a corrected PMV for more accurate thermal sensation predictions. Non-air-conditional buildings, categorised by location and warm periods, are allocated with different expectance factors, as shown in Table 2.2.

<table>
<thead>
<tr>
<th>Expectation</th>
<th>Classification of non-air-conditioned buildings</th>
<th>Warm periods</th>
<th>Expectancy factor, ( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>In regions where air-conditioned buildings are common</td>
<td>Occurring briefly during the summer season</td>
<td>0.9–1.0</td>
</tr>
<tr>
<td>Moderate</td>
<td>In regions with some air-conditioned buildings</td>
<td>Summer season</td>
<td>0.7–0.9</td>
</tr>
<tr>
<td>Low</td>
<td>In regions with few air-conditioned buildings</td>
<td>All seasons</td>
<td>0.5–0.7</td>
</tr>
</tbody>
</table>

Departure from comfort may also lead to consciously or unconsciously lowering activity levels (Baker and Standeven, 1996; Fanger and Toftum, 2002). Hence, Fanger and Toftum (2002) suggested a decline of 6.7% in metabolic rate for every unit increase in PMV above zero (i.e. metabolic rate would unconsciously reduce by 6.7% when PMV is 1.0 and by 10% when PMV is 1.5), and therefore people could tolerate higher temperature.

2.7.2 Adjustments based on empirical statistics
Humphreys and Nicol (2002) proposed a revised PMV model to better match the calculated PMVs with the actual mean votes provided in ASHRAE databases of field-studies. The statistic-
based revision relies on a variable of $D_{PMV-ASHRAE}$, which relates to environmental factors and occupants’ characters (shown in Equation 2.1), and then a new PMV can be calibrated using Equation 2.2.

$$D_{PMV-ASHRAE} = -4.03 + 0.949T_{op} + 0.00584 \times RH\% + 1.201 \times \text{(met * clo)} + 0.000838 \times T_{out}^2$$  
(Equation 2.1)

$$PMV_{new} = 0.8 \times (PMV - D_{PMV-ASHRAE})$$  
(Equation 2.2)

Where, $T_{op}$ is operative temperature, RH% is relative humidity, met is metabolic rate, col is clothing level and $T_{out}$ is outdoor mean air temperature.

The authors emphasised that the purpose of the revised model was just to illustrate a possible approach to improving the PMV model rather than to replace the original model, since they believe that the rational PMV model should be modified in terms of its psychological and physiological and physical-physiological structures but not simply based on empirical statistics (Humphreys and Nicol, 2002).

### 2.7.3 Adaptive Predicted Mean Vote (aPMV)

Yao et al. (2009) proposed the Adaptive Predicted Mean Vote (aPMV) model. In comparison to the revision introduced by Humphreys and Nicol (2002), Yao et al.’s revision was also based on data from field studies but just focuses on a specific region. The proposed aPMV model is as below:

$$aPMV = \frac{PMV}{1 + \lambda \times PMV}$$  
(Equation 2.3)

Where $\lambda$ is called adaptive coefficient, which relates to occupants’ psychological and behavioural adaptations as well as culture, climate and social factors.

Based on numerous field studies in Chongqing and Beijing in China, Yao et al. (2009) and Xu
et al. (2010) derived expressions of aPMV for Chongqing and Beijing respectively:

\[
aPMV = \frac{PMV}{1 + 0.293 \cdot PMV} \quad \text{(warm conditions for Chongqing, China)} \tag{Equation 2.4}
\]

\[
aPMV = \frac{PMV}{1 - 0.125 \cdot PMV} \quad \text{(cold conditions for Chongqing, China)} \tag{Equation 2.5}
\]

\[
aPMV = \frac{PMV}{1 + 0.285 \cdot PMV} \quad \text{(warm conditions for Beijing, China)} \tag{Equation 2.6}
\]

\[
aPMV = \frac{PMV}{1 - 0.136 \cdot PMV} \quad \text{(cold conditions for Beijing, China)} \tag{Equation 2.7}
\]

2.8 Summary

This chapter reviews physiological adaptations, psychological adaptations, thermal comfort models, stochastic behaviour models, MM buildings, passive energy-saving strategies and the developments on the existing static thermal comfort models. It indicates that physiological adaptations play an insignificant role in one’s adaptation to a moderate environment and psychological adaptations are abstract and their effectiveness may vary significantly in different scenarios. It also shows that mixed mode building and passive energy-saving strategies have a great potential for energy conservation. Moreover, stochastic behaviour models can attain more reliable results of building energy simulations in comparison with traditionally used diversity profiles. This strength may be even more remarkable for a building with abundant control opportunities and largely relying on passive techniques (Hoes et al., 2009). Stochastic behaviour models may also be suitable for the robustness analysis of design solutions. Additionally, stochastic behaviour modelling can assist to explore in-depth effects of user behaviour on building performance and the relation between a building and its users. An application of a stochastic behaviour model is presented in Chapter 6.Apart from the PMV model and adaptive models, there are other in-between approaches to determining thermal comfort, such as the ePMV and aPMV models.
Chapter 3 – A theoretical study on the quantification of adaptive thermal comfort

3.1 Introduction of this chapter

As discussed in Chapter 2, steady-state models do not contain adaptive processes and adaptive models cannot explicitly evaluate individual adaptive opportunities. Hence, both kinds of thermal comfort models may not be applicable to all the situations with different levels of adaptations. This chapter proposes an alternative method of predicting adaptive thermal comfort based on the availability of adaptations, in particular behavioural adaptations, which needs quantifications of individual adaptation processes and of interactions between them. The fundamental argument of this method is that exercising an adaptive behaviour leads to an increase in comfort temperature, which is termed adaptive increment in this study. Apart from adaptive increments, this method also determines a baseline thermal comfort temperature (the thermal comfort temperature without adaptations) and a correction factor that considers the factors affecting adaptive behaviours, based on which, the highest operative temperature at which people may still feel thermally comfortable. This method is believed to be flexible in dealing with different environments with various levels of adaptations and likely to be advantageous over the steady-state and adaptive models in predicting thermal comfort temperature of an environment with abundant adaptive opportunities.

As discussed in Chapter 2, physiological adaptations play an insignificant role in one’s adaptation to a moderate environment and psychological adaptations are abstract and their effectiveness may vary significantly in different scenarios. Behavioural adaptations, on the other hand, are virtual and their effectiveness are widely recognised, and have already been quantitively studied in previous literature (Baker and Standeven, 1996; Oseland et al., 1998; Haldi and Robinson, 2008). Hence, adaptive increments associated with behavioural adaptations are the focus of this study. This chapter attempts to develop the understanding
of behaviours adaptations and present a detailed quantification of behaviours adaptations. This is achieved via a thorough analysis of previous literature, the SET* mode and CFD simulations. CFD simulations are conducted on an office environment to explore how physical conditions of the environment would be affected by exercising adaptive behaviours. The interactions among adaptive behaviours are also studied in detail by using the SET* model and CFD simulations.

3.2 The alternative method of predicting adaptive thermal comfort

In previous studies, Baker and Standeven (1996) and Oseland et al. (1998) proposed that adaptive increments resulted from different adaptive behaviours can be added together for simplicity. However, it is clear that this simplification is not robust as the adaptive increments may be influenced by interactions among adaptive behaviours, constraints of adaptive behaviours, and physiological and psychological adaptations. An example of the interaction between adaptive behaviours is that an occupant with low ‘clo’ values will be more susceptible to adjustments in air movement. A possible constraint is that a window is not easily openable, leading to a reduced benefit of window operation. Also, exercising an adaptive behaviour may have both physical and psychological consequences. The physical consequences include changes in personal and environmental factors such as changes in metabolic rate and air velocity, whereas the psychological consequences may consist of modified perceived control and expectations which may either improve or dampen the corresponding adaptive increment. A positive physiological adaptation may also further extend the adaptive increment. To deal with these factors, a correction factor is proposed.

The alternative method of predicting adaptive thermal comfort proposes that the adaptive increments of individual adaptive behaviours are added up to form an overall adaptive increment. It is then multiplied by an empirical correction factor to obtain a corrected overall adaptive increment, which is added to the baseline comfort temperature to get an adaptive comfort temperature. This study firstly presents a detailed analysis of adaptive behaviours and their quantifications via analysis of previous literature, the SET* model and CFD
simulations, followed by an examination of the interactions among various adaptive behaviours. Users’ preferences over a range of behaviour adaptive opportunities, baseline thermal comfort temperature, the correction factor and the application of the alternative method of predicting adaptive thermal comfort will then be discussed in detail.

3.3 Method
As mentioned above, exercising adaptive behaviours would lead to the modifications in environmental or personal variables, whose contributions to thermal comfort improvements are quantified using the SET* model. The quantifications of behavioural adaptations are supported by CFD simulations conducted on an office environment to capture some detailed effects of exercising an adaptive behaviour on its thermal environment. A typical naturally ventilated building model, as shown in Figure 3.1, is used for CFD simulations. The model is a part of a large open plan office, including a cellular office and its surrounding corridor. Only south and north walls of the model are exposed to the exterior. Analyses mainly focus on single-sided ventilation taking place in the cellular office, and the surrounded corridor is used for cross ventilation analysis. This building model is based on the one used in the study of Rijal et al. (2007) who claim that it is a typical model used by UK practitioners for energy consumption benchmarking.

![The cellular office](image)

**Figure 3.1. Sketch of the typical naturally ventilated building model.**

The floor to ceiling height of the model is 3 m. The floor areas of the cellular office and the corridor are 22.5 m² and 67.5 m² respectively. The areas of the two south facing windows are
both 3.6 m² and the corridor has a large north facing window of 7.8 m². All doors are measured at 0.9 m * 2.1m height. The construction details are shown in Figure 3.2.

![Figure 3.2. Constructions details of wall, floor and ceiling. Values represent thickness which is in millimetres Rijal et al. (2007).](image)

The commercial CFD code, ANSYS Fluent, is used for this study. The computational domain includes both indoor and outdoor environments of the building, whose dimensions, as shown in Figure 3.3, are determined following the guideline presented in the work of Franke et al. (2011).

![Figure 3.3. The computational domain.](image)
In terms of meshing, grids are refined around openings, fan, people and walls in order to explicitly characterise the features of air flows close to these objects. The total number of grids is about two million. For each simulation, a converged solution is obtained when all residuals reduce to at least 0.001 until these residuals have stabilised.

As this study concentrates on indoor flow patterns, the chosen RNG k-ε turbulence model could provide reasonable results with acceptable computing cost. The SIMPLE algorithm is adopted for pressure-velocity coupling. Discretization scheme pressure equation is solved using the Body Force Weighted scheme, whereas all other equations (momentum, temperature, k and ε) are solved using second-order upwind schemes. As for buoyancy-only cases, none-slip walls are used for outer CFD domain boundaries. In order to analyse the combined stack and wind effects, a logarithmic wind profile at the inlet boundary layer is used (Liddament, 1986). It assumes that the building is located in urban, so wind speed in accordance with height can be calculated as below:

\[ V = 0.35V_{10}h^{0.25} \]

Where \( V_{10} \) is the wind speed measured at the meteorological site at the standard height of 10 m and \( h \) is the height in question.

The temperatures of room walls are maintained at 26°C while the external temperature is set to 22°C, representing a typical summer morning condition suggested by Caciolo et al. (2013). The boundary condition of the ceiling fan is modelled by the fan boundary model in ANSYS Fluent. Yan et al. (2009) and Villi and De Carli (2013) argue that a simplified human model could lead to acceptable global simulation results and is even capable of capturing features of local human environment provided that human boundary conditions are properly assigned. In this study, a simplified human model made up of blocks is used. Radiation is simulated by using the surface-to-surface radiation model embodied in ANSYS Fluent. The effect of solar radiation is neglected.
3.4 Behaviour adaptations

Adaptive behaviours will be, either consciously or unconsciously, exercised by occupants when they are exposed to heat stress. Adaptive behaviours may be divided into three categories, personal (e.g. adjusting clothing and position), technical (e.g. operating a fan and a window) and cultural behaviours (e.g. having a siesta). Adaptive behaviours also include operating HVAC system, but this study focuses on increasing thermal comfort temperature to reduce the reliance on HVAC system so that HVAC operations are not evaluated in detailed.

There are a number of studies attempted to quantify adaptive behaviours (Rohles et al., 1983; Baker and Standeven, 1996; Oseland et al., 1998; Brager et al., 2004; Robinson and Haldi, 2008; Robinson and Haldi, 2010; Liu et al., 2013). Commonly evaluated adaptive behaviours include window operation, fan operation, door operation, having cold drinks and clothing adjustment.

Table 3.1 illustrates the derived adaptive increments from different studies, and considerable variations among these values have been noticed. This may be explained by the fact that the magnitude of an adaptive increment is closely related to the features of the adaptive behaviour which can be case sensitive. For example, the adaptive increment due to fan operation is significantly affected by the resulted air velocity and can be different from site to site, leading to a large variance in adaptive increment. An important point to note is that exercising an adaptive behaviour may lead to both physical and psychological consequences.

Exercising the adaptive behaviours related to controls may to some extent contribute to perceived control and in turn enhance thermal comfort. Liu et al. (2013) argue that operating windows and doors predominantly lead to psychological related adaptive increments, whereas the physical consequences of clothing adjustment and fan usage are overwhelming.

| Table 3.1. Adaptive increments obtained in field studies |
|-----------------|------|-----|------|---------|------|
|                 | Window | Fan | door | Cold drink | clothing |
| Rohles et al.   | - | 3°C | - | - | - |
| (1983)          |      |     |     |       |      |
| Baker and       | - | - | - | 0.7 | - |
| Standeven (1996)|      |     |     |       |      |
| Oseland et al.  | 1.1 | 2.2°C - 2.8°C | - | 0.9 | 6.54/clo |
| (1998)          |      |     |     |       |      |
Apart from the above widely recognised adaptive behaviours, there are other adaptive behaviours which may also contribute to thermal comfort, including blind control, activity adjustment, clothing adjustment, using a net (non-upholster) chair, posture adjustment, temporal and locational adaptations. Following sections evaluate each adaptive behaviour in detail and propose a guidance value/scope of the adaptive increment for each adaptive behaviour.

### 3.4.1 Window operation

Window operation is a common and effective adaptive process in naturally ventilated buildings to enhance occupants’ thermal comfort. An opening window can let in fresh and cool air, provided that outdoor temperature is lower than indoor temperature. Even though outdoor temperature is high, occupants may still open window to increase indoor air movement, which can improve evaporative cooling, and prevent solar radiation from being trapped indoor. Window operation can increase one’s neutral temperature by 1.58°C observed by Brager et al. (2004) and between 0.5°C and 1.1°C in the study of (Haldi and Robinson, 2008). A theoretical study is conducted to evaluate these benefits based on CFD simulations.

According to Figure 3.4 and Figure 3.5, air speed around the human body is elevated when the occupant is sitting by the window and the occupant enjoys a lowered local temperature in comparison to the case that the occupant is sitting in the middle of the room. It is worth noting that solar radiation is not included in the study, so in practice, the magnitude of the

<table>
<thead>
<tr>
<th>SCATs database*</th>
<th>1.1</th>
<th>1.25</th>
<th>0.29</th>
<th>-</th>
<th>4.46/clo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brager et al. (2004)</td>
<td>1.58</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Robinson and Haldi (2008)</td>
<td>0.5-1.1</td>
<td>1.39</td>
<td>0.15</td>
<td>0.69</td>
<td>-</td>
</tr>
<tr>
<td>Liu et al. (2013)</td>
<td>1.1</td>
<td>1.3</td>
<td>0.8</td>
<td>-</td>
<td>4.1/clo for winter 7.5/clo for summer and the whole year</td>
</tr>
</tbody>
</table>

* Values estimated using the assumption of Griffiths by Haidi and Robinson (2010) based on the Smart Controls and Thermal Comfort (SCATS) database (Nicol and McCartney, 2001)
reduction in local temperature may be smaller, while and the magnitude of air speed elevation may be larger (due to the larger temperature gradient between indoor and outdoor). Moreover, internal gain, window size, distance to the window, wind speed and direction will all influence local temperature and air speed. An important point to note is that the temperature reduction in the area near window leads to spatial variation which may trigger occupants’ locational adaptation. Hence, the adaptive increments of window operation can be induced by both air speed elevation and locational adaptations.

Figure 3.4. A comparison of air speed distributions for the cases of the occupants sitting by the window (the upper one) and in the middle (the lower one).
Figure 3.5. A comparison of temperature distributions for the cases of the occupants sitting by the window (the upper one) and in the middle (the lower one).

In order to quantify the effect of elevated air speed, an overall air speed is required for SET* calculations. However, air patterns around a human body are highly asymmetric and different parts of a human body have different perceptions of air speed. According to Henry (1918), the density of sweat glands is much higher in hand, forehead, forearm and chest than that in back and legs. Also, Hertzman and Randall (1948) state that skin of head and hands with only 7% of total skin area takes up 25%-27% of total skin blood flow and is always exposed to ambient air. Hence, the evaporative cooling due to air movement should be more effective on upper body, in particular at the face level, which can explain the phenomenon that air registers of HVAC systems are usually oriented towards occupants’ faces (De Dear, 2009). For these
reasons, the adaptive increment associated with window opening can be more accurately estimated by using a multi-node comfort model. In this case, according to Figure 3.4, local air speed is estimated to rise from 0.1 m/s to 0.2 m/s for an occupant sitting near the window. Such elevated air speed is equivalent to an increase in SET* of 0.8°C, based on the environmental conditions of the CFD simulations (air and radiant temperature of 24°C at 50% RH) and typical office users (1.2 met and 0.7 clo). Additionally, according to Figure 3.5, local temperature of the occupant sitting near the window is also asymmetric with low temperature observed at the body trunk at the window side. An overall local temperature reduction can be at least 0.5°C. An important point to note is that window operation may contribute to psychological adaptations (e.g. naturalness perception and perceived control), leading to a psychological adaptive increment.

In summary, if an occupant is sitting by a window, his/her local thermal environment may change significantly once the window is open. If he/she can easily operate the window, remarkable psychological benefits may also be induced. In this study, an overall adaptive increment of 1.5°C is highly likely to be achievable (by considering interactions between these benefits and one may dampen another to some extent). This estimation is based on a large window opening area, considerable lower outdoor temperatures than indoor and no constraint of using the window. However, internal gain, window size, distance to the window, wind speed and direction will all influence local temperature and air speed, and people may perceive the psychological benefits differently. Hence, the adaptive increment due to window operation varies significantly from site to site as indicated in Table 3.1 and should be carefully evaluated before application. Based on the previous literature and this study, the range of the adaptive increment associated with window operation from 0.5 to 1.58°C is taken for guidance.

3.4.2 Fan operation
Fan operation is an effective and energy efficient way to increase room air movement and therefore enhance occupants’ thermal sensation. Various studies have shown that both
personal and ceiling fans can efficiently improve occupant thermal comfort. In this section, the benefits of using a ceiling fan are studied.

3.4.2.1 Effects of fan location on local air speed

In order to evaluate the effects of ceiling fan locations on human local air movement, two cases are derived. In the first case, the fan is centrally mounted at the height of 2.5 m directly above the human model. In the second case, the fan is located at the same position, but the human model is moved to the side of the room. For both cases, the studied room model with a closed window is the same as the one presented in Section 2. The position of the ceiling fan is based on the suggestion of Aynsley (2007) that a ceiling fan will have the best performance when the floor to ceiling height is at least 3m with a clearance of 0.5m from the ceiling.

A common 3-Speed ceiling manufactured by Monte Carlo Ceiling Fan Company is chosen. The diameters of the total fan surface and hub are about 1.32 m and 0.3 m respectively. The relationships among volume flow rate through the fan surface, Rotation Per Minute (RPM) and power are shown in Table 3.2.

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Median</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume flow rate produced (m$^3$/s)</td>
<td>2.38</td>
<td>1.62</td>
<td>0.77</td>
</tr>
<tr>
<td>RPM</td>
<td>188</td>
<td>131</td>
<td>67</td>
</tr>
<tr>
<td>Power (W)</td>
<td>60.5</td>
<td>31.5</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Source: http://www.build.com/mediabase/specifications/mc_5wf52bk_spec.pdf

The results of CFD analysis displayed in Figure 3.6 which indicates that the ceiling Fan would have good performances when it is mounted directly above the occupant, whereas only lower parts of the occupant may benefit from the air movement induced by the fan if it is mounted far away (even if fan is operating at a higher speed for the latter case). This is in good agreement the findings in Samer et al. (2011). Hence, the best location of a ceiling fan should be direct above the seats of occupants.
Figure 3.6. Air speed contours showing air speed distribution for two cases (fan is operating at medium mode in the upper picture and at high mode in the lower picture).

Other features of the air plume generated by a ceiling fan, which cannot be seen from the Figure 3.6, include it could be highly turbulent and air speed at any point experiences a large uncertainty over time (Rohles et al., 1983; Aynsley and Ali, 2004; Samer et al., 2011). These features, as argued by Rohles et al. (1983), are important parts of a ceiling fan’s comfort-producing capability and may enhance one’s preference of ceiling fan over other air-moving devices.

3.4.2.2 General relationship between comfort temperature and air speed elevation caused by a fan
Rohles et al. (1983) did an experiment to explore the effects of elevated air speed on one’s comfort acceptability and found that the upper limit of the comfort zone can be extended from an effective temperature of 26°C to 29°C when air speed increases to 1m/s, respectively. However, the study was based on the air velocity data measured in a non-occupied room at a single height of 1.1m. Further studies are required to evaluate to what degree the measured air velocity is in consistent with the overall air speed perceived by an occupant.

ASHRAE standard 55 (2010) suggests the upper limit of air speed for light primarily sedentary activity to be 0.8m/s, although further elevation in air speed could continue to offset temperature increment. This may be because higher air movement can cause general disturbance and pressure on the skin (Toftum, 2004), or light objects would be blown away at high speed. However, this will not happen under at least 1m/s indicated by the results of the experiment of Rohles et al. (1983).

3.4.2.3 Adaptive increments associated with fan operation

In order to quantify the effect of ceiling fan operation, it is necessary to determine the overall air speed resulted from fan operation. The case that the ceiling fan mounted directly above the occupant with the medium operating speed (1.63 m³/s) is used for analysis. According to the upper picture of Figure 3.6, the induced air speed around the upper body is about 0.9-1.0 m/s whereas the lower body experience a much lower air speed. The average room air speed is assumed to be approximately 0.8 m/s, which is in good agreement to the study of Ward et al. (2012) who suggests a ceiling fan producing 1.4 m³/s volume flow rate leads to an average room air speed of 0.8 m/s.

To relate the elevated air speed with an adaptive increment, the diagram named ‘air velocity required to offset increased temperature’ included in ASHRAE standard 55 (2010) and ISO 7730 (2005) is used, as shown in Figure 3.7. This diagram is derived by using the SET* model and it also includes the influences of the difference between air temperature and radiant temperature. Although this correlation is based on a theoretical model, it has been
experimentally validated by Toftum and Melikov (2000). According to Figure 3.7, an air speed of 0.8 m/s induced by fan operating will lead to an adaptive increment of about 2.5°C, and this adaptive increment can further increase when the fan operates at a higher speed. It is worth noting that the differences in thermal sensation caused by types of fans (ceiling fan, ceiling jet and desk fan) and turbulence intensity errors (deviation between actual ones and the ones involved in the SET* model) may be negligible (Huang et al., 2014). Since the adaptive increment associated with fan operation is highly influenced by the magnitude of the air speed generated by the fan, the adaptive increment should be carefully evaluated for a case study. Based on the previous studies as shown in Table 3.1 and this study, the range of the adaptive increment associated with fan operation from 1.25 to 3°C is taken for guidance.

Figure 3.7. Air velocity required for offsetting temperature increase.

3.4.3 Door operation
When both doors and windows are opened, cross ventilation may be activated. Similar to window operation alone which result in single-sided ventilation as discussed in Section 3.4.1, door operation may also lead to local temperature reduction, air speed increase and psychological benefits. The results of CFD simulations of cross ventilation is presented in
Figure 3.8 and Figure 3.9. By comparing Figure 3.8 and Figure 3.4, it can be concluded that cross ventilation significantly increases indoor air movement. Moreover, by comparing Figure 3.8 and Figure 3.5, the case with cross ventilation would have an averagely over 1°C decrease in room temperature than the case with single-sided ventilation. Other studies have similar results. Raja et al. (2008) found that the cross ventilation induced by opening both door and window could lead to a 1.1°C drop in indoor temperature which is comparable to the value observed by Raja et al. (2001). According to Figure 3.8, the overall air speed rise to about 0.4 m/s (high air movement occurs at the head and upper body level), which is equivalent to an adaptive increment of approximately 1.5°C according to Figure 3.7.

However, a few field studies showed that door operation does not have a statistically significant correlation with either indoor or outdoor temperature (Raja et al., 2001 and 2008; Haldi and Robinson, 2008 and 2010). One possible reason for this is that door operation is usually exercised when occupants are leaving or entering the room rather than for the purpose of cooling. Hence, it is doubtful whether door operation will improve perceived control and it also may not enhance the naturalness perception. The psychological effects of door operation need further justifications.

Despite the psychological benefits, the physical benefits of door opening together with window opening to form cross ventilation would perhaps lead to an increment of 2.5°C which is 1°C higher than window opening alone. It is worth noting that the effect of cross ventilation is dependent on a range of factors, such as the temperature gradient between indoor and outdoor, building layout, wind speed etc., and therefore can vary considerably. Based on the previous studies as shown in Table 3.1 and this study, a range of the adaptive increment associated with door operation alone (deducting the benefits of window operation) from 0.15 to 1°C is taken for guidance.
Figure 3.8. Air speed vectors for the cross ventilation case (the cross-section is at the level of 1.1 m).

Figure 3.9. Temperature vectors for the cross ventilation case.
3.4.4 Blind control

Properly designed blinds/shading devices would effectively reduce direct radiation on a human body as well as limit solar heat gain. According to Baker and Standeven (1995), occupants who are exposed to direct radiation will have about 1°C higher perceived temperature than that those who are well protected from direct radiation will have in the same environment. A similar value is observed by Haldi and Robinson (2008).

However, both Haldi and Robinson (2010) and Schweiker et al. (2013) found blind/shading device control action is not strongly correlated to indoor or outdoor temperatures. This is reasonable as occupants will usually use blind to prevent glare rather than solar heat gain. An important point to note is that closed blinds (either internal or external) may affect air penetrations through windows and therefore decrease the effect of natural ventilation.

3.4.5 Activity adjustment

Metabolic rate is a key variable for thermal comfort. Metabolic rate values are commonly estimated based on surveyed occupants’ self-reported activity levels. However, this method is problematic as it does not distinct mechanical power from heat production and work for respiration and circulation and overlooks the fact that metabolic rate can vary for the same task (Baker and Standeven, 1996). Occupants exposed to heat stress may unconsciously lower their metabolic rate which could be subtle for sedentary office activities and therefore this adjustment cannot be fully revealed by using the method based on self-reported activities (Fanger and Toftum, 2002). Above arguments may justify the reasons why metabolic rates and thermal stimuli are always reported to be independent of each other (de Dear et al., 1997; Bouden and Ghrab, 2005), whereas, in fact, the change in metabolic rate is an adaptive behaviour to heat exposure. In order to accurately assess the effects of this adaptive behaviour, more detailed methods, such as heart rate measurement and direct calorimetry as described in Table 3.3, should be used.
Alternatively, Baker and Standeven (1996) used a body mass model and time-lapse photography to estimate metabolic rate. Behaviours of body masses, expressed as terminal velocities captured by time-lapse photography, are weighted according to muscular efficiency and summed up to determine metabolic rate. For a sedentary office work, vigorous and lethargic movements would result in a difference in metabolic rate by about 10%, which can be translated into an adaptive increment of 0.7 °C (Baker and Standeven, 1995).

Table 3.3. Different methods of determining metabolic rate (ISO 8996, 2004).

<table>
<thead>
<tr>
<th>Level</th>
<th>Method</th>
<th>Accuracy</th>
<th>Inspection of the work place</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Screening</td>
<td>1A: Classification according to occupation</td>
<td>Rough information</td>
<td>Not necessary, but information needed on technical equipment, work organization</td>
</tr>
<tr>
<td></td>
<td>1B: Classification according to activity</td>
<td>Very great risk of error</td>
<td></td>
</tr>
<tr>
<td>2: Observation</td>
<td>2A: Group assessment tables</td>
<td>High error risk</td>
<td>Time and motion study necessary</td>
</tr>
<tr>
<td></td>
<td>2B: Tables for specific activities</td>
<td>Accuracy: ± 20%</td>
<td></td>
</tr>
<tr>
<td>3: Analysis</td>
<td>Heart rate measurement under defined conditions</td>
<td>Medium error risk</td>
<td>Study required to determine a representative period</td>
</tr>
<tr>
<td></td>
<td>Accuracy: ± 10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4: Expertise</td>
<td>4A: Measurement of oxygen consumption</td>
<td>Errors within the limits of the accuracy of the measurement or of the time and motion study</td>
<td>Time and motion study necessary</td>
</tr>
<tr>
<td></td>
<td>4B: Doubly labelled water method</td>
<td>Accuracy: ± 5%</td>
<td>Inspection of work place not necessary</td>
</tr>
<tr>
<td></td>
<td>4C: Direct calorimetry</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4.6 Clothing adjustment

3.4.6.1 Features of clothing insulation

Clothing level is a determinant variable for thermal comfort. The overall clothing value is estimated by summing up the insulation of individual garments given in standard tables (ASHRAE, 2010). However, this numerically cumulative insulation value of a given clothing ensemble may have high deviation since actual insulation is also influenced by body posture, the pumping effect of the clothing and the ‘wick effect’ of fibres (Berger, 1988). For example, the typical loose clothing with multiple-layers in some hot dry climate is more effective in heat exchange than what the insulations of the materials indicate. It can not only prevent skin from ambient high temperature and solar radiation but also provide adequate air layers allowing for pumping effect and promoting evaporative heat loss (Berger, 1988).
3.4.6.2 Clothing adjustment outline

Clothing adjustment is an effective adaptive behaviour in respond to thermal stimuli. A range of studies tried to find the relationships between clothing insulation level and monthly mean (or running mean) outdoor temperatures or indoor temperatures using linear regression (De Dear and Brager, 1998; Nicol et al., 1999; De Carli et al, 2007; Haldi and Robinson, 2011; Schweiker et al., 2013). However, all of these linear relations could not achieve a very high quality of fit. In order to more accurately estimate clothing adjustment from thermal stimuli, it may be necessary to distinct from within-day adjustment to day-to-day adjustment. Many researchers found that within-day adjustment (in terms of summertime, some occupants would like to wear two layers and remove one layer when feeling warm) is rarely exercised (Baker and Standeven, 1997; Barlow and Fiala, 2007; Haldi and Robinson, 2008). This may be a result of fashion concerns, strict dress code or office culture. However, subtle adjustments, such as shortening sleeves, rolling up pants legs and opening shirt collar, are more frequently made (Haldi and Robinson, 2011). Haldi and Robinson (2011) suggested that these small adjustments could lead to a 0.1 clo change in the clothing insulation level. Day-to-day adjustment, on the other hand, is highly dependent on thermal stimuli. Morgan and de Dear (2003) and Schweiker et al. (2013) related clothing insulation to the average outdoor temperature of the previous day and forecast maximum temperature of the current day. Haldi and Robinson (2011) elaborated a more detailed model that even takes into consideration environmental factors and context-specific constraints.

3.4.6.3 Adaptive increment associated with clothing adjustment

The adaptive increments associated with both large and subtle clothing adjustments are calculated using the SET* model. CIBSE (2006) suggested the typical summertime insulation level for an office dress is 0.7 clo which is used for the base case. Although within-day large clothing adjustment is seldom observed in terms of a whole-day analysis, the probability of exercising this adjustment may increase considerably when extreme thermal conditions appear, provided that no strict dress code is required and the occupant wear two layers. When
the large adjustment is exercised, the clothing value is assumed to reduce from 0.7 clo to 0.5 clo, which leads to an adaptive increment of 1.4°C. In terms of subtle clothing adjustment, the clothing value is assumed to reduce from 0.7 clo to 0.6 clo, which is equivalent to an adaptive increment of 0.7°C. Based on the previous studies as shown in Table 3.1 and this study, the range of the adaptive increment associated with clothing adjustment from 4.46 to 7.5 °C/clo is taken for guidance.

3.4.7 Posture adjustment

3.4.7.1 Posture and effective body surface

Posture adjustment alters the effective body surface area which is highly related to metabolic rate. People usually extend their body in a hot environment and on the other hand curl up when feeling cold. Hence, posture adjustment can be an important adaptive behaviour, but it is always paid little attention to in many thermal comfort studies. Additionally, in many thermal comfort indices, the total surface area (usually calculated using the DuBois’s equation (DuBois and DuBois, 1916) for a standing person) is used rather than the effective surface area corresponding to a given posture (Raja and Nicol, 1997).

In order to evaluate the effective body surface area of different postures, Raja and Nicol (1997) developed the posture recording scheme. The scheme assigns each body segment with a standard area, based on which the covered area due to the contact of two body parts (\(A_{mc}\)) and the contact between body parts and other surfaces (\(A_{tC}\)) of most sedentary postures can be determined. Using this scheme and visual/video observations, Raja and Nicol (1997) analysed the correlation between body surface area and indoor temperature at Oxford Brooks University. Results show that both \(A_{mc}\) and \(A_{tC}\) are strongly correlated with indoor temperature, as illustrated in Figure 3.10. Wyon and Holmberg (1972) also found that as indoor temperature increases from 20°C to 30°C, children gradually increase their body surface area through posture adjustments.
Figure 3.10. The relationships between indoor temperature and the covered area due to the contact of two body parts ($A_{mc}$) and the contact between body parts and other surfaces ($A_{tc}$) as a percentage of total body surface area.

3.4.7.2 Posture and clothing insulation level

Body postural change also affects clothing insulation (Olesen et al., 1982; Berger, 1988; Baker and Standeven, 1997). Olesen et al. (1982) found that, based on the analysis using a manikin, there is an 8-18% decrease in intrinsic clothing insulation values for sitting in comparison to standing. In comparison, Havenith et al. (1990) observed a 13-16% decrease in intrinsic clothing insulation and a reduction of 4-18% in total insulation. Olesen et al. (1982) and McCullough et al. (1994) argued that the decrease in clothing insulation was attributed to the compression of clothing, causing reduced air trapped in clothing layers. An important point to note is that the decrease in clothing insulation due to sitting posture may be offset by additional chair insulation (Olesen et al., 1982).

3.4.7.3 Adaptive increment associated with posture change

In this section, the difference in effective body surface between a normal sitting posture and an assumed relaxed sitting posture due to heat stress is calculated using the posture recording scheme developed by Raja and Nicol (1997). The scheme uses a six-digit code to represent a posture. Each digit corresponds to a body part and each body part has several positions for selection, as shown in Table 3.4. Each body part is assigned with a projected area (the
maximum area may be covered by another body part or an external surface as a percentage of the total body surface area), which is used to determine the covered area of that body part for each posture. The total covered area is calculated by summing up the covered area of each part. More details about the scheme can be found in Nicol and Raja (1997) and Raja and Nicol (1997). Descriptions and calculated results of the normal sitting posture and assumed relaxed sitting postures are shown in Table 3.4.

Table 3.4. Definitions of the six digits in the code.

<table>
<thead>
<tr>
<th>Digit number</th>
<th>Body part</th>
<th>Number of choices</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Position of head and neck</td>
<td>Three</td>
</tr>
<tr>
<td>Second</td>
<td>Position of the left upper limb (left upper arm, forearm and hand)</td>
<td>Nine</td>
</tr>
<tr>
<td>Third</td>
<td>Position of the right upper limb</td>
<td>Nine</td>
</tr>
<tr>
<td>Fourth</td>
<td>Position of the trunk</td>
<td>Four</td>
</tr>
<tr>
<td>Fifth</td>
<td>Position of pelvis</td>
<td>Four</td>
</tr>
<tr>
<td>Sixth</td>
<td>Position of thighs and legs</td>
<td>Four</td>
</tr>
</tbody>
</table>

Table 3.5. A comparison between the normal sitting posture and the assumed relaxed sitting postures.

<table>
<thead>
<tr>
<th>Corresponding code</th>
<th>The common sitting posture</th>
<th>The relaxed sitting posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position of head and neck</td>
<td>Free head and neck (not resting on a support)</td>
<td>Free head and neck</td>
</tr>
<tr>
<td>Position of the left upper limb (left upper arm, forearm and hand)</td>
<td>upper arm (left) touching the body &amp; forearm resting on support</td>
<td>forearm (left) resting on support</td>
</tr>
<tr>
<td>Position of the right upper limb</td>
<td>Upper arm (right) touching the body &amp; forearm resting on support</td>
<td>forearm (right) resting on support</td>
</tr>
<tr>
<td>Position of the trunk</td>
<td>Leaning backwards on a support,</td>
<td>Free trunk</td>
</tr>
<tr>
<td>Position of pelvis</td>
<td>Sitting to the back of a chair</td>
<td>Sitting on front edge</td>
</tr>
<tr>
<td>Position of thighs and legs</td>
<td>Legs crossed (close)</td>
<td>Legs apart</td>
</tr>
<tr>
<td>Covered area due to body contact</td>
<td>13.68%</td>
<td>0%</td>
</tr>
<tr>
<td>Covered area by external area</td>
<td>13.7825%</td>
<td>7.43%</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>Total covered area</td>
<td>27.4625%</td>
<td>7.43%</td>
</tr>
</tbody>
</table>

It is worth noting that covered area due to body contact affects convective and evaporative heat transfer, whereas covered area by external area is related to conductive heat transfer. The conductive heat transfer is neglected here and therefore the relaxed sitting posture has 13.68% less covered area compared to the common sitting posture. However, the increase in effective body surface area would also lead to a slight rise in clothing insulation due to increased air boundary layer and looseness of clothing, which will to some extent offset the benefits of this posture adjustment on neutral temperature increment. Hence, based on the 11% increase in body exposed surface area (which is approximately equivalent to a decrease of 10% in metabolic rate), the adaptive increment is estimated, to be 0.7°C.

3.4.8 Using a net (non-upholster) chair
Chair insulation value should be added to the clothing insulation to form an overall insulation level. However, as discussed above, the chair insulation roughly compensates the reduced clothing insulation resulted from a sitting posture. In this study, using a net chair is regarded as an adaptive behaviour. If it is applied, the base case clothing level of 0.7 clo will reduce to 0.6 clo (a typical chair insulation of 0.1 clo is assumed (McCullough et al, 1994), leading to an adaptive increment of 0.7°C.

3.4.9 Having cold drinks
Having cold drinks is a frequently exercised adaptive activity in a hot environment (Haldi and Robinson, 2011). The benefit of having cold drinks is reducing one’s metabolic rate. Schweiker et al. (2013) reported an approximate increase of 0.1L in the cold drink taken for every 1°C rise in indoor operative temperature. Haldi and Robinson (2011) found that the probability of cold drink consumption strongly correlated with both indoor temperature and outdoor running mean temperature. Baker and Standeven (1996) presented a method to quantify the effects of having cold drinks on the reduction in metabolic rate. They estimated that if 330ml
of a cold drink at 5°C is taken hourly, the body will be provided with a cooling effect of 12 W, which is equivalent to a decrease of 10% in metabolic rate in terms of an averaged sitting person. This decrease in metabolic rate is equivalent to an adaptive increment of 0.7°C. Based on the previous studies as shown in Table 3.1, the range of the adaptive increment associated with having a cold drink from 0.5 to 0.9°C is taken for guidance.

3.4.10 Temporal and locational adaptations
Temporal adaptation can be defined as the adjustment of occupants’ working time to escape from extreme working conditions. Locational adaptation is caused by spatial variation, presuming that occupants would make small movements of positions to a cooler space or/and where these is an air stream. Newsham (1992) used a computational tool to model occupants’ mobility within a large room and predict thermal comfort level of mobile occupants. Results showed that mobile occupants were significantly more thermally comfortable than occupants fixed at the centre of the room. The conclusion was confirmed by PASCOOL comfort surveys (Baker and Standeven, 1995) which showed that the average room temperature would be 0.5°C to 1.5°C higher than local operative temperatures around occupants. A typical adaptive increment of 1.25°C associated with temporal and locational adaptations is suggested by Baker and Standeven (1995).

However, due to workplace culture, such as fixed working hours and set team arrangement, temporal and locational adaptations are highly restricted (Barlow and Fiala, 2007; Healey and Webster-Mannison, 2012). Also, Procter and Fennell (2011) pointed out that economic concerns on office overheads also limited temporal and spatial adaptations in the UK context.

3.4.11 Summary of the adaptive increments associated with adaptive behaviours
Table 3.6 summarises the derived adaptive increment of each adaptive behaviour in previous sections together with brief explanations.
Table 3.6. Summary of the adaptive increments.

<table>
<thead>
<tr>
<th>Adaptive behaviour</th>
<th>Adaptive increment</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window operation</td>
<td>0.5 to 1.58 °C</td>
<td>It is largely attributed to psychological benefits and slightly attributed to physical benefits; high psychological benefit; Highly case sensitive</td>
</tr>
<tr>
<td>Fan operation</td>
<td>1.25 to 3 °C</td>
<td>Largely related by the air speed generated</td>
</tr>
<tr>
<td>Door operation</td>
<td>0.15 to 1 °C</td>
<td>Door opening works with door opening to form cross ventilation; Highly case sensitive</td>
</tr>
<tr>
<td>Blind control</td>
<td>1 °C</td>
<td>Highly deceasing radiant temperature</td>
</tr>
<tr>
<td>Activity adjustment</td>
<td>0.7 °C</td>
<td>Reducing metabolic rate by about 10%</td>
</tr>
<tr>
<td>Clothing adjustment</td>
<td>4.46 to 7.5 °C/clo</td>
<td>Expressed as adaptive increment per unit clothing level change; case sensitive</td>
</tr>
<tr>
<td>Posture adjustment</td>
<td>0.7 °C.</td>
<td>Based on an estimation of 11% increase in body exposed surface area, equivalent to a decrease of 10% in metabolic rate</td>
</tr>
<tr>
<td>Using a net chair</td>
<td>0.7 °C.</td>
<td>Based on a change in a typical chair insulation of 0.1 clo</td>
</tr>
<tr>
<td>Having cold drinks</td>
<td>0.5-0.9 °C.</td>
<td>May be explicitly estimated through the amount of drink taken hourly according to Baker and Standeven (1996)</td>
</tr>
<tr>
<td>Temporal and locational</td>
<td>1.25 °C.</td>
<td>suggested by Baker and Standeven (1995); case sensitive</td>
</tr>
<tr>
<td>adaptations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.5 Interactions among adaptive behaviours

A human body is a highly integrated system, so the change of one parameter could influence many other parameters. For example, a certain amount of increase in temperature may not result in the same shift in thermal perception at different humidity and air velocity. Similarly,
when two or more adaptive behaviours are exercised simultaneously, the overall adaptive increments may be either larger or smaller than the sum of individual increments. Both CFD simulations and the SET* model are used to analyse the combined effects of two or more adaptive behaviours in this section. An important point to note is that it assumes that solar radiation is well controlled in the base case. If an occupant is exposed to direct solar radiation and does not have the control over blind, there will be a decrease in neutral temperature.

The adaptive behaviours, with typical adaptive increments according to the above analysis included in brackets, are divided into four groups in terms of the environmental/personal variables they affect as below. It is worth noting that psychological effects of exercising adaptive behaviours are not considered here and, as discussed above, window opening and door open can both affect air movement and local temperatures.

- Air speed: fan operation (2.5°C), window opening (0.8 °C), door opening (0.7°C)
- Clothing insulation level: clothing adjustment (0.7-1.4°C), using a net chair (0.7°C)
- Metabolic rate: cold drink (0.7°C), activity (0.7°C), posture (0.7°C).
- Local temperature: Blind control (affecting radiant temperature) (1 °C), window opening (0.5°C), door opening (0.5), locational adaptations (1.25°C)

3.5.1 interactions among adaptive behaviours within the same group

In the clothing level modification group, the adaptive increments due to clothing adjustment and using a net chair are considered independent to each other. In the air speed modification group, all the three factors interact with each other. By comparing Figure 3.11 and Figure 3.4, the air speed induced by the ceiling fan is dominant when the ceiling fan and the window are operated simultaneously.
The metabolic rate change is highly related to the occupant’s thermoregulatory system which could be sensitive to any changes within the body, so how the factors in the metabolic rate modification group can be very difficult to determine. In practice, the situation would occur that a person is slowing his/her motion and simultaneously drinking cold drink and changing posture, so, in this study, the three factors are considered independent to each other.

In the local temperature modification group, all the three factors interact with each other. For instance, if blind control is not available, the benefit of low temperature near the window due to window opening will be offset by the temperature increase at the area due solar heat gain. Also, as a locational adaptation, an occupant may move to the area near an opened window, but the one would not do so if there is no blind available to control strong solar radiation.

### 3.5.2 Interactions among adaptive behaviour groups and between the groups and the indoor environment

The clothing insulation level modification group is slightly affected by the metabolic rate modification group, for instance, postural change (having less contact with the chair) may dampen the benefit of the use of a net chair. The air speed modification group is considerably influenced by all other groups. How indoor temperature and humidity may influence the
effects of adaptive behaviours and users’ preferences over different adaptive behaviours are also analysed.

### 3.5.2.1 The effects of indoor temperature and humidity on adaptive increments

According to the SET* model, indoor temperature and humidity have limited effect on the adaptive increments caused by clothing insulation and metabolic rate modifications, since properties of clothing insulation and metabolic rate are relatively independent of environmental variables. On the other hand, indoor temperature (e.g. the relationship between air temperature and radiant temperature) and humidity more considerably influence the effects of locational adaptation and air speed elevation. Occupants would usually choose to stay in a place where both indoor temperature and humidity conditions are satisfactory. Details about how indoor temperature and humidity conditions affect the benefits of air speed elevation are discussed below.

### 3.5.2.2 Effects of operative temperature on the benefits of air speed elevation.

In the SET* model, convective heat transfer is dependent on the convective coefficient which is set to be in proportion to air speed when air speed is over about 0.2m/s. According to the SET* model, the variance in operative temperature has little effect on the benefits of air speed elevation. A possible explanation is discussed below. Within the operative temperature range from 22°C to 35°C, as operative temperature increases, convective heat loss is reduced due to the smaller gradient between skin and operative temperatures. This reduction will be less significant at high air speed due to the increase in convective coefficient. Meanwhile, skin wettedness also increases, leading to an increase in evaporative heat loss which to some extend offset the reduction in convective heat loss.

### 3.5.2.3 Indoor relative humidity and the effect of air speed elevation.

The efficiency of evaporative cooling is dependent on the difference between saturated vapour pressure at skin temperature and partial pressure at air temperature. For higher relative humidity (at an air temperature below the skin temperature), the efficiency of
evaporative cooling is lower (Evans, 1982; Scheatzle et al., 1989; Kimura et al., 1993; Berger, 2001). Hence, the effect of elevated air speed on improving thermal comfort would be weakened at high relative humidity. As the SET* model takes account of the vapour permeability properties of clothing and responds well to the change of relative humidity (Gagge et al., 1986), it should be a useful tool to predict the effect of high relative humidity on the benefits of air speed elevation. Based on the SET* model, when relative humidity increases from 50% to 80%, the adaptive increment due to the increase in air speed from 0.2 m/s to 0.8 m/s reduces from 2.2°C to 1.8°C.

3.5.2.4 Interactions between the local temperature modification and air speed modification groups

Factors in the local temperature modification group would either change local air temperature or radiant temperature and, in turn, adjust the difference between air temperature and radiant temperature. This difference would influence the effects of air speed elevation, as shown in Figure 3.7. If an occupant is exposed to direct solar radiation, leading to a high radiant temperature experienced by the occupant, the effect of elevated air speed will considerably reduce. Air speed elevation will also be less effective in a room with high thermal mass, where the radiant temperature is usually dominant in hot weather. This is supported by Tony Isaacs Consulting Pty Ltd (2006) who found fans are generally more frequently turned on in rooms with higher thermal mass. However, if the thermal mass is effectively cooled down by means of night ventilation, air speed elevation would play a more important role.

When a fan is turned on, the cooler air near the window is circulated deep into the room, leading to more incoming outdoor cool air. This phenomenon can be detected by comparing Figure 3.12 and Figure 3.4. Since a ceiling fan will result in well-mixed indoor air, locational adaptation may not be very effective in a room with a ceiling fan turned on.
3.5.3 The combined effect of elevated air speed and reduced metabolic rate on the overall adaptive increments

According to the SET* model, the effectiveness of evaporative cooling is largely dependent on skin wettedness which is determined by the amount of regulatory sweating. Generally, when the operative temperature is below 25°C, the amount of regulatory sweating of an occupant with a typical summer office dress (e.g. 0.7 clo) remains at a very low level. As operative temperature increases over 25°C, the amount of regulatory sweating grows accordingly. Provided that other environmental factors and clothing level remain constant, the dropped metabolic rate (due to having cold drinks and activity adjustment) leads to a reduction in the amount of regulatory sweating, which, in turn, lowers the benefits of air speed elevation. Apart from reducing skin wettedness, posture adjustment also increases exposed skin surface, which would enhance the efficiency of air speed elevation.

On the other hand, adaptive increment due to lowered metabolic rate, which is partially resulted from the reduction in skin wettedness, will be dampened at a high air speed. Hence, if an adaptive behaviour from the air speed modification ground is exercised mutually together with one behaviour from the metabolic rate modification ground, the adaptive increments induced by individual adaptive behaviour will both reduce. Quantitatively, based on the SET* model, the adaptive increments due to the increase in average air speed from

![Figure 3.12. Temperature contour for the case that ceiling fan and window are operated simultaneously.](image-url)
0.2m/s to 0.8m/s at a range of metabolic rate from 0.85 met to 1.2 met are shown in Figure 3.13, whereas the adaptive increments due to 10% reduction in metabolic rate at a range of air speed from 0.2m/s to 1.2m/s are shown in Figure 3.14. Both Figure 3.31 and Figure 3.14 clearly quantitatively illustrates that when elevated air speed and reduced metabolic rate occur simultaneously, the combined adaptive increments will be dampened.

It is worth noting that within the range from 25°C to 30°C, an air speed of 1 m/s has already resulted in a very low skin wettedness, and therefore the increase in air speed may not further dampen to the effect of lower metabolic rate.

![Figure 3.14. The relationship between air speed elevation and metabolic rate.](image-url)
3.5.4 The combined effect of elevated air speed and reduced clothing insulation on the overall adaptive increments

Based on the SET* model, the adaptive increments due to the increase in average air speed from 0.2m/s to 0.8m/s at three clothing levels are shown in Figure 3.15. As indicated by the Figure 3.15, reduced insulation level slightly increases the benefit of air speed elevation. However, as discussed above, some subtle clothing adjustments, such as shortening sleeves and open collar, could increase exposed skin area, which could considerably contribute to the effect of air speed elevation (ASHRAE, 2006). However, the effect of the increase in exposed skin area is not accounted by the SET* model as it integrates a relatively simple clothing model which cannot adequately distinct clothed skin from exposed skin. Hence, the adaptive increments should be more significantly accentuated by lowered clothing level than what is indicated by the Figure 3.15. It is perhaps promising to use multi-node comfort models for this issue.
Figure 3.15. Relationship between adaptive increment associated with air speed elevation and clothing insulation level.

The interactions among adaptive behaviours within the same group and among groups are summarised in Figure 3.16. If individual behaviours or behaviour groups interact with each other, they are connected by two arrow lines.
Figure 3.16. Interactions among adaptive behaviours within the same group and among groups.

3.5.5 Summary of the interactions among adaptive behaviours

A human body is a highly integrated system, so the change of one parameter could influence many others. For example, increases in temperature may not lead to the same shift in thermal perception at different humidity and air velocity. Similarly, when two or more adaptive behaviours are exercised simultaneously, the overall adaptive increment may be either larger or smaller than the sum of individual increments. The SET* model is used to analyse the combined effects of adaptive behaviours. The SET* model works to convert the six basic thermal stimuli to a single operative temperature (at RH 50%) at which individuals with standardised metabolic rate and clothing will have the same skin wettedness and skin temperature (Gagge et al., 1986). This, in turn, determines the amount of operative temperature increase that can be offset by using an adaptive behaviour (namely the adaptive increment of using an adaptive behaviour). This method has already been used to estimate the offsets of operative temperature increase due to air speed elevation (ASHRAE, 2013; ISO 7730, 2005). Huang et al. (2014) are among those who experimentally verify the applicability
of the SET* model in predicting the effects of air movements on occupants’ thermal sensation. The SET* model is based on a two-node human physiological model, so it can imitate the physiological reactions when two or more adaptive behaviours are exercised together.

According to the SET* model, air velocity is positively correlated with the effectiveness of evaporative cooling in this case as participants’ metabolic rate are at a low level. Evaporative cooling, or evaporative heat transfer at the skin surface, is also largely dependent on skin wettedness which is determined by the amount of regulatory sweating. Generally, when the operative temperature is below 25°C, the amount of regulatory sweating of an occupant with a typical summer office dress (e.g. 0.7 clo) remains at a very low level. As operative temperature increases over 25°C, the amount of regulatory sweating grows accordingly. Provided that other environmental factors and clothing level remain constant, the dropped metabolic rate (due to having a cold drink) leads to a reduction in regulatory sweating, which, in turn, weakens the enhancement in evaporative cooling due to air velocity increase. Since metabolic rate has little to do with dry heat transfer from skin to outer environment and respiratory heat loss can be negligible at low metabolic rate compared to evaporative heat transfer at skin surface and dry heat transfer from skin, it can be deduced that when having a cold drink and desk fan usage are exercised simultaneously, the overall adaptive increment will be smaller than the sum of the individual ones.

The SET* model also suggests that clothing levels are negatively correlated with the effectiveness of evaporative cooling. Hence, on the condition that other environmental factors remain constant, the reduced metabolic rate (due to having a cold drink) leads to a reduction in skin wettedness, which, in turn, lowers the enhancement in evaporative cooling due to clothing level decrease. Therefore, when having a cold drink and taking off clothing are exercised simultaneously, the overall adaptive increment will be less than the sum of individual ones.

The effectiveness of the increase in air movement will be enlarged as one’s clothing level
decreases because reduced clothing level will usually increase exposed skin area. However, a desk fan is mainly acting on the exposed skin of the head, and therefore its effectiveness is to a small extent influenced by clothing adjustments. Hence, when taking off a shirt, having cold water, using desk fan and using cool mat are exercised simultaneously, the overall adaptive increment should be noticeably less than the sum of individual corresponding adaptive increment, which can somehow explain the aforementioned discrepancy between the theoretical and actual overall adaptive increments.

3.6 Users’ preferences over a range of behaviour adaptive opportunities

When a range of opportunities to adapt are available, occupants’ preferences over these choices may be dependent on ease of use, the effectiveness of the opportunities and economic concerns (Hwang et al., 2009). Occupants probably prefer the most convenient opportunities to the logically most effective controls (Leaman, 1999), and are generally not willing to sacrifice their thermal comfort to save energy at the workplace (Hwang et al., 2009). However, economic concerns seem to play a very important role in the residences (Feriadi and Wong, 2004). Hence, office users would probably choose their preferred adaptive options based on the ease of use principle, but uncertainty could be very high. The uncertainty may be even higher for some partially unconscious adaptive behaviours like posture adjustment and activity level change. Generally, window opening, fan operation, clothing adjustment and having cold drinks are four most frequently excised adaptive behaviours in naturally ventilated buildings, but the ranking of these adaptive behaviours differs among different field studies.

Some field studies found environmental adjustment (window opening and fan operation) are most often excised options (Wong et al., 2002), whereas other field studies found clothing adjustment was the most popular one (Wei et al., 2010; Liu et al., 2012b). These discrepancies may result from the differences in studied time of year and climate between these field studies, and perhaps more likely from constraints of adaptive options. For example, rain and outdoor noise may affect the usage of windows, and a strict dress code may influence clothing
adjustment. Hence, in order to model occupants’ adaptive behaviours using the above model, constraints over the adaptive behaviours should be paid close attention to.

3.7 Baseline neutral operative temperature

The baseline thermal comfort temperature can be determined by using the Fanger’s PMV model (Baker and Standeven, 1996). However, people will usually feel comfortable throughout a range of temperatures instead of at a single temperature. Nicol and Humphreys (2009) argue that a temperature drift of 1°C from a customary temperature has hardly any influence on thermal comfort but when it increases to 2°C discomfort and complaints would begin to occur. This is consistent with field study result that there is a 2°C swing in one’s neutral temperature (Baker and Standeven, 1996), and also in line with field observations on window operations which showed that occupants will usually not open window until the operative temperature is about 2°C higher than the neutral temperature (Rijal et al., 2007 and 2008). This delay of action may be attributed to the capability of human thermoregulation system or the so-called thermoneutral zone (TNZ). The TNZ can be defined as the range of ambient temperatures at which the body thermoregulation only relies on vasomotor control, leading to sensible (conductive, convective and radiative) heat loss, without modifying metabolic heat production and evaporative heat transfer (perspiration) (Kingma et al., 2012b). The TNZ found by Kingma et al. (2012b) ranges from 23.5°C to about 26°C for an average person with clothing insulation of 0.7 clo. This indicates that at 26°C a person will have a very low skin wettedness which is a key indicator of thermal comfort (Gagge et al., 1986). Hence, 26°C can be regarded as a typical crisis point of thermal discomfort or the upper limit of the baseline comfort zone.

However, it is worth noting that individual differences in comfort acceptability could be significant. According to Kingma et al. (2012b), the TNZ is dependent on subcutaneous fat thickness and age. Field studies also found that age would affect thermal acceptability (Rohles et al., 1983; Lenzuni et al., 2009; Matos de Carvalho et al., 2013) and that gender may be another factor (Bischof et al., 2002; Lan et al., 2008; Choi et al., 2010). Rohles (2007) proposed
a relationship between individual difference and temperature, as shown in Figure 3.17, which implies that the difference in thermal sensation is significant at moderate temperatures but gradually reduces towards extreme conditions. Hence, an upper limit of the comfort zone increased by adding adaptive increments may apply to the most people.

![Figure 3.17. The relationship between individual difference and temperature (Rohles, 2007).](image)

3.8 The empirical correction factor

As discussed in Sections 3.5, interactions among adaptive behaviours commonly exist, and using one adaptive behaviour is more likely to dampen the effectiveness of another rather than contributing to it. Individual adaptive behaviour may be also restricted by constraints (e.g. strict dress code, indirect access to controls and unsatisfied outcome of control actions), and therefore the magnitude of the corresponding adaptive increment would be reduced. Additionally, the magnitude of the overall adaptive increment may be either increased or reduced with the effects of positive or negative psychological adaptations. As mentioned above, physiological adaptations merely have effects on extreme conditions, so acclimated people may further extend their upper comfort limit. This may be partially explained by the fact that elevated air speed has a more significant effect on an acclimated people with higher core temperature and increased sweat volume. Among the factors affecting the overall adaptive increment, interactions among adaptive behaviours may be inevitable, whereas
constraints of adaptive behaviours, psychological and physiological adaptations may vary from site to site.

Both Haidi and Robinson (2008) and Haidi and Robinson (2010) attempted to derive individual adaptive increments of available adaptive behaviours and the overall adaptive increment. The relationship between the sum of individual adaptive increments and the overall adaptive increment is evaluated to provide some guidelines to determine the range of the correction factor. The field study of Haidi and Robinson (2008), which was conducted in Switzerland, derived the adaptive increments of five adaptive behaviours with the average values in bracket: window operation (0.58°C), blind control (0.46°C), fan operation (1.39°C), door opening (0.15°C) and having cold drinks (0.69°C). The overall adaptive increment obtained from the field study is 2.85°C, which is divided by the sum of the above individual adaptive increments (3.27°C) to get a correction factor of 0.89. Haidi and Robinson (2010) analysed the SCAT database (field studies conducted in France, Greece, Portugal, Sweden and UK) to derive adaptive increments of five adaptive behaviours with the average values in bracket: window operation (1.1°C), clothing adjustment (2°C) and fan operation (1.4°C). The overall adaptive increment obtained from the field study is 4.3°C, which is divided by the sum of the above individual adaptive increments (4.5°C) to get a correction factor of 0.96.

One issue of the two field studies is that they did not consider some personal adaptive processes such as activity variation, posture adjustment, temporal and locational adaptations which may increase the sum of the individual adaptive increments and in turn lower the correction factor. Moreover, since the study of Haidi and Robinson (2008) was conducted in naturally ventilated two-person private offices, the occupants can easily operate windows and other controls and would enjoy a good level of perceived control and natural perception which will probably lead to positive psychological adaptations. Hence, the correction factor could be smaller in other cases with less favourable environmental conditions. Window operation, blind control, temporal and locational adaptations may be easily subject to constraints and artificial environments (air-conditioned space) may lead to negative psychological effects.
Based on the above analysis, a correction factor, ranging from 0.5 to 1, is proposed to reflect different levels of interactions of constraints of adaptive behaviours, psychological and physiological. The value of 0.5 denotes that the adaptive behaviours adversely affect each other, and there are noticeable constraints, highly negative psychological and physiological adaptations. The value of 1 represents that interactions among adaptive behaviours are limited and there are ignorable constraints, highly positive psychological and physiological adaptations. The feasibility of this range requires more case studies to improve.

3.9 Applications of the alternative way of predicting adaptive thermal comfort

There are increasing interests exerting on the development of MM buildings, in particular the changeover type of MM building. Occupants of this type of buildings rely on natural ventilation and other possible adaptive opportunities to achieve thermal comfort at moderate conditions and are supported by an air conditioning (AC) system at extreme conditions. In order to balance the trade-off between maintaining thermal comfort and energy conservation, it is crucial to determine an appropriate temperature changeover point. This temperature can be regarded as the upper comfort temperature limit of occupants in the mode of free-running which can be determined by using the alternative way of predicting adaptive thermal comfort. Determining such upper comfort temperature limit requires investigations of interactions among adaptive behaviours, constraints of adaptive behaviours, psychological and physiological adaptations, which will be discussed later in this section.

The following study is to demonstrate how the above method may be applied. The baseline comfort zone (includes a baseline neutral operative temperature and the baseline acceptability range), within which no adaptive behaviour will be exercised, is firstly designated. This is followed by the determination of the additional comfort zone due to the cumulative adaptive increments for a typical free-running buildings case.
The baseline neutral comfort operative temperature in this study refers to the neutral operative temperature for the office occupant engaged in a sedentary activity (1.2 met) in a still air environment (airspeed is 0.1 m/s) with a relative humidity of 50%. The overall insulation of a typical office outfit for summertime is 0.7 clo (shirt, trousers, underwear, socks and shoes), and a common insulation value for an office chair is 0.1 clo (ISO 7730, 2005). Using these parameters as input for the Fanger’s PMV model, a baseline comfort operative temperature of 24°C can be obtained.

An office in Athens from the database of the PASCOOL programme (Baker and Standeven, 1994) is used for illustrating the applications of the adaptive increments. This office is naturally ventilated, allowing all the behaviour adaptations mentioned in Section 3.4 except for fan and door operation. Clothing adjustment changes the clothing level from 0.7 clo to 0.4 clo, leading to an adaptive increment of 2.1°C. Louvre blinds are used for shading control, but once they are deployed ventilation and a view out are obstructed. The base case assumes that the solar radiation is well controlled, so deploying louvre blinds will lead to a negative value of adaptive increment. The cumulative adaptive increment is 7.15°C, leading to a modified comfort temperature of 31.15°C, as shown in Table 5.1. Baker and Standeven (1994) found that 89% of the occupants accept the thermal environment at an indoor average temperature of 30.5°C, indicating an overall adaptive increment of 6.5°C. This gives the correction factor of 0.91.

<table>
<thead>
<tr>
<th>Available adaptive opportunities (estimated adaptive increment °C)</th>
<th>cumulative adaptive increment</th>
<th>Upper comfort limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>An Office in Athens</td>
<td>Window (+1.5) posture (+0.7), activity (+0.7), chair (+0.7), drink (+0.7), clothing adjustment (+2.1), temporal and locational adaptations (+1.25), blind (-0.5)</td>
<td>7.15</td>
</tr>
</tbody>
</table>
3.10 Discussion

Above studies indicate that the effectiveness of behavioural adaptations is significant provided that they are not inhibited by control constraints, negative psychological physiological factors. It is no doubt that one’s personal variables and his/her local physical environments benefit significantly from abundant behavioural adaptations, which also contributes to one’s psychological adaptations, in particular the categories of perceived control and naturalness & environmental stimulations. Behavioural adaptations can be quantified by using adaptive increments, which can be theoretically derived by manipulating parameters in a steady-state thermal comfort model (Baker and Standeven, 1996; Oseland et al., 1998) or obtained from field studies (Haldi and Robinson, 2008; Haldi and Robinson, 2010; Liu et al., 2013).

The theoretically derived adaptive increments may overlook the effects of control constraints, negative psychological and physiological factors. The ones obtained from field studies also have some shortcomings that these values are based on a limited size of dataset and they are derived without considering the variations of surveyed subjects’ clothing level, metabolic rate and local temperature (Haldi and Robinson, 2010). Moreover, as environment conditions and occupant behaviours are not controlled in field studies, it is difficult to the evaluate the exclusive adaptive increment of an adaptive behaviour free from the interference of other adaptive behaviours (Haldi and Robinson, 2010). Hence, it is necessary to validate the obtained adaptive increments through more controllable field studies and experiments or using more detailed multi-node models rather than the simple steady-state models. An important point to note is that the adaptive increment can be highly case sensitive, and the guidance values and ranges obtained in this study should be carefully revised to suit specific cases.

Based on derived adaptive increments, a novel way of determining adaptive thermal comfort is proposed. The other two parts of the method, the baseline thermal comfort temperature and the correction factor, also need more investigations to improve their feasibility. As
mentioned above, the baseline thermal comfort temperature can be determined by using the Fanger’s PMV model (Baker and Standeven, 1996). However, due to considerable variations in thermal comfort temperature, it is preferable to survey the thermal comfort temperature of the occupants in question.

The proposed range of the correction factor needs further justifications to validate. More efforts are required to study the effects of interactions among adaptive behaviours, constraints of adaptive behaviours, psychological and physiological adaptations. Although the above factors may not be easily quantified at this stage, it is of importance to promote positive psychological and physiological adaptations and remove control constraints so that the effects of behaviour adaptations will not be inhibited. Suggestions for improving psychological and physiological adaptations and removing control constraints are listed below:

- Visual friendly decorations, proper office layout and indoor plants.
- Good view out and friendly light environment
- Good air quality and noise control.
- Providing shower room, changing room, hot/cold water machine, flexible working stations, removable furniture and petitions, good access to outdoors and transitional spaces (e.g. atria).
- No strict dress code.
- Providing personal, highly responsive and easily accessible controls (Some effective state-of-art personal comfort devices, such as a heated/cooled chair (Pasut et al., 2015) and footwarmers (Taub et al., 2015) should be paid more attention to).

3.11 Summary
This chapter proposes an alternative method of predicting adaptive thermal comfort. According to Chapter 2, physiological and psychological adaptations are abstract, and it is very difficult to quantify their effectiveness. Behavioural adaptations, on the other hand, are virtual and their effectiveness are widely recognised, and therefore are the main components of the
method. Adaptive increments of ten adaptive behaviours are investigated by using the SET* model and CFD simulations on the basis of previous literature. The obtained adaptive increments may be case sensitive and perhaps vary among different groups of occupants, so further studies are required to validate them. The other two parts of the method, the baseline thermal comfort temperature and the correction factor, are also analysed in detail. The range of the correction factor should be further validated through more detailed studies on interactions among adaptive behaviours, constraints of adaptive behaviours, psychological and physiological effects when exercising adaptive behaviours.

The advantage of this novel method over the widely used PMV model and adaptive models is that it reveals the effects of individual adaptation process and therefore is capable of evaluating a complicated building with abundant available adaptive opportunities. This feature gives the method a large potential to determine an appropriate changeover point of MM buildings. Additionally, this method can provide some insightful guidelines for designing NV and MM buildings. Further researches in the following chapters, including experimental justifications and field studies, are conducted to reinforce this novel method.
Chapter 4 - A laboratory study on the quantification of adaptive thermal comfort

4.1 Introduction of this chapter

The previous chapters introduced adaptations and has also quantified individual adaptive behaviours and evaluated factors affecting adaptive increments through theoretical studies. This chapter introduces a lab experiment that adopts a climate chamber with human subjects to verify and develop the results of the theoretical study. The use of climate chambers is criticised as treating occupants as passive recipients of the given thermal environment since a climate chamber usually does not provide conditions for adaptive behaviours and separates the indoor environment from outdoor, thus limiting behavioural and psychological adaptations (de Dear et al., 1997). However, the main advantage of using a climate chamber is that many variables can be controlled and influencing factors can be limited so that the effects of specific behavioural options can be isolated. Additionally, a climate chamber provides a relatively uniform environment, avoiding the issue that one’s local temperature may differ from the one obtained at the monitoring point in field studies.

This study aims to test and quantify to what extent a range and combination of adaptive opportunities can determine comfort, and thus add to our understanding of the explicit mechanisms that underpin adaptive comfort. The aim would be achieved by the following objectives:

- Identify effective behavioural and psychological adaptations;
- Determine the adaptive increments of the effective behavioural and psychological adaptations
- Analyse and quantify the interactions among adaptations;
- Determine the highest operative temperature at which people may still feel thermally comfortable when abundant adaptations are available.
- Evaluate the preferences for various adaptive behaviours.
- Provide guidance of taking full advantage of adaptive behaviours in practice.
4.2 Method

4.2.1 Adaptive behaviours

The adaptive behaviours in question can be divided into three categories, namely:

1) Physical items
2) Personal behaviours
3) Building related factors

This study focuses on the first two categories. Physical items include desk fan usage, clothing adjustment, having cold water, cool mat usage and wet wipe usage. The cool mats, as shown in Figure 4.2.4, used in this study are bamboo brick seat covers which are cool in warm environments since bamboo is a natural heat insulation material. The wet wipes, as shown in Figure 4.2.4, are refreshing facial cleansing wipes used for removing sweat and enhancing evaporation from faces. Personal behaviours consist of body posture adjustment, activity variation and having a sleep. Building related factors are opening windows, blind operation and locational adaptations (seeking for a cooler environment), but this category of adaptive behaviours has not been assessed here due to the limitations of the laboratory facilities (i.e. there is no window available in the climate chamber and the uniform thermal environment disables locational adaptations).

4.2.2 Climate chamber

The climate chamber used in this research is located in the Department of Building Science, Tsinghua University. As shown in Figure 4.2.1, it has two separately controlled rooms both measuring at 5 m * 3 m * 2.7 m (height). Air is supplied uniformly from the ceiling plate and returns through the raised floor with an air change rate of up to 0.75 ac/h. A stable and uniform environment can be maintained, and the precision of controlled air temperature and relative humidity are ±0.5 °C and ±5% respectively. Both rooms have a total of 10 sensors mounted at different locations in the chamber, and two portable hygrothermographs are also used to measure air temperature and relative humidity of both rooms for verification purposes.
4.2.3 Experimental setups

This study was divided into a dynamic study and a static temperature study. The dynamic study was firstly conducted and raised some questions that require detailed and targeted static temperature experiments to answer. The dynamic study contains an experiment in which air temperature is gradually increasing. The static temperature study contains eight separate experiments, and each looks at an environmental condition with a fixed air temperature and certain sets of adaptive behaviours. For each experiment, participants were recruited separately by sharing recruitment information in WeChat groups (WeChat is the most popular social media in China). The experiments were conducted on different days in September of 2015. All the recruited participants are students from Tsinghua University or nearby universities. Every participant was given a remuneration of 40RMB per hour. Detailed experimental set-ups for the dynamic study and the static temperature study are described separately in the following two sections.
4.2.3.1 Experimental set-up 1 (dynamic study)

The dynamic study aimed to test the set-up and establish the temperatures at which occupants feel thermally comfortable. Instead of looking at a particular temperature, this study was conducted in a transient thermal environment. The room air temperature gradually increases from 24°C to 32°C over a period of two hours. The temperature starts at 24°C, and gradually rises to 26°C over 20 minutes before the temperature remains constant for the following 10 minutes. This process is repeated in 2°C increments up to 32°C.

A total of 19 university students participated in this first experiment, and they were allowed to exercise the adaptive behaviours mentioned below. Participants are videoed throughout the experiment progress to capture their adaptive behaviours, such as clothing adjustment, body posture adjustment, activity variation, periods of sleep and using wet wipes. A questionnaire, shown in Appendix 4.1, is used to collect basic information of participants, including gender, height, weight and age. It also evaluates the participants’ thermal sensation and acceptability of the thermal environment, as well as their perceptions of air quality and desk fan usage. The ASHRAE 7-point thermal sensation scale, a thermal acceptability scale with degree of significance and an air quality acceptability scale with degree of significance are adopted. The thermal acceptability scale with degree of significance can collect detailed information how participants find the environments and has been used in Zhang and Zhao (2008), Zhang et al. (2010), Zhai et al. (2013) and Luo et al. (2015). Each participant was asked to fill in corresponding parts of a questionnaire at the beginning of the experiment as well as at the end of each temperature of 26°C, 28°C, 30°C and 32°C. Figure 4.2.2 illustrates the experimental progress. Figure 4.2.3 shows the view of an ongoing experiment and Figure 4.2.4 illustrates major adaptive opportunities.

![Figure 4.2.2. Illustration of the experiment progress of the dynamic study.](image-url)
The dynamic study evaluated the percentage of participants that regard the thermal environment as acceptable, the thermal sensation vote (TSV), Predicted Mean Vote (PMV) and the percentage of participants using each adaptive behaviour. The input parameters (i.e. clothing level, metabolic rate and air speed) used for PMV calculations will be modified when one or several adaptive behaviour(s) are exercised. The changes to input parameters are based on empirical values from previous literature, which are explained in detail later in this section. When calculating PMVs, an initial metabolic rate of 1.0 met is taken since participants
were mainly reading or using the internet during the experiment. An air speed of 0.05 m/s and 50% relative humidity are used for the experimental room. According to previous literature (Yamtraipat et al., 2005; Walikewitz et al., 2015), the radiant temperature is presumed to be equal to the air temperature.

According to video recordings, no obvious body posture adjustment or activity variation is detected, and very few participants had a snooze or used a wet wipe, so the effects of these adaptive behaviours are neglected. On the other hand, the remaining adaptive behaviours of clothing level, air speed and metabolic rate values used for PMV calculations are presented below:

**Clothing level** Dress code is not specified in the dynamic study (i.e. experiment participants are not restricted to a particular dressing style). Thermal insulation of participants’ clothing is calculated based on the standard of ISO 7730 (2005), ranging from 0.38 clo to 0.73 clo (including the chair’s extra effective clothing level of 0.08 clo). It is worth noting that clo values obtained from tables of clothing insulation for ensembles and garment are designed for a standing position, while a seated position reduces clothing insulation due to the decrease in insulation resulted from the air layer surrounding the body and in air trapped in the clothing (McCullough et al., 1994). However, this reduction can be balanced out with the additional insulation provided by a metal chair under the condition of summer dressing (McCullough et al., 1994). Compared with a metal chair, a computer chair, similar to the ones used in the experiment, has the additional insulation of 0.08 clo (McCullough et al., 1994). Each participant is asked to put on a cotton shirt (0.25 clo) over their own clothing at the beginning of the experiment, and he/she was allowed to remove the shirt at any time during the whole process. Examples of cotton shirts can be found in the Figure 4.2.3 (they are hanging on the back of chairs). The removal of the shirt converts to a reduction of thermal insulation value of 0.25 clo, while either shortening sleeves or unbuttoning converts to a decrease of 0.05 clo.

**Metabolic rate** During the experiment, cold water is available directly from a refrigerator and
its temperature is around 5°C. Cold water was refilled by one of the authors every 10 minutes and was kept cool by continuously adding ice. According to Baker and Standeven (1996), keeping having a cold drink of 330ml at 5°C within an hour is equivalent to approximately 10% reduction in one’s metabolic rate. The input metabolic rate for the PMV calculation would be calibrated based on the amount of the cold water taken in proportion to that value.

**Air speed** A personal desk fan adopted in the experiment, measuring a diameter of 20cm, can generate an air speed of 1.0 m/s at the face level measured by an anemometer, Testo 405-V1, as shown in Figure 4.2.5. However, this air speed cannot be directly applied as a desk fan just has effects on head level, and, rather, an overall air speed over a human body is required for the PMV calculation. Some previous studies have attempted to determine the equivalent overall air speed created by a desk fan. According to Table 4.2.1, Oseland et al. (1998) argue that a change in air speed by 2 m/s induced by using a desk fan leads to an adaptive increment of 2.8°C. The desk fan used in this study, which generates 1 m/s air speed, is approximately half as effective as the one in the study of Oseland et al. (1998) and therefore results in an adaptive increment of about 1.4°C. This value is in accordance with the study of Atthajariyakul and Lertsatittanakorn (2008) who evaluated the effects of desk fans on Thai people and obtained a neutral temperature of 27.4°C at the local air speed of 1 m/s and a neutral temperature of 26°C at the local air speed of 0.2 m/s. An adaptive increment of 1.4°C is equivalent to an overall air speed increase of around 0.4 m/s according to Figure 4.2.6 which is obtained from the ASHRAE standard 55 (ASHRAE, 2013). Hence, an increase in the overall air speed by 0.4 m/s is used for PMV calculations in this study as a result of using a desk fan.
Table 4.2.1. Adaptive increments from previous literature.

<table>
<thead>
<tr>
<th>Adaptive increment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7°C (Oseland et al., 1998)</td>
<td>Changes Clothing level by -0.26</td>
</tr>
<tr>
<td>0.3°C (Oseland et al., 1998)</td>
<td>Changes Clothing level by -0.05</td>
</tr>
<tr>
<td>≈0.7°C (Baker and Standeven, 1996)</td>
<td>Reduce metabolic rate by 10%</td>
</tr>
<tr>
<td>0.9°C (Oseland et al., 1998)</td>
<td>Changes metabolic rate by -0.12</td>
</tr>
<tr>
<td>0.69 ± 0.12°C (Haldi and Robinson, 2008)</td>
<td>-</td>
</tr>
<tr>
<td>2.8°C (Oseland et al., 1998)</td>
<td>Change air speed by +2.0 m/s</td>
</tr>
<tr>
<td>2.2°C (Oseland et al., 1998)</td>
<td>Change air speed by +1.0 m/s</td>
</tr>
<tr>
<td>1.39 ± 0.39°C (Haldi and Robinson, 2008)</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 4.2.5. Testo 405-V1 anemometer.
4.2.3.2 Experimental set-up 2 (static temperature study)

In order to more explicitly explore the effectiveness of adaptive behaviours, and to find out the highest temperature at which participants may still feel thermally comfortable, each experiment in the study was carried out at one constant temperature. According to the analysis of the dynamic study (which will be discussed in more detail in Section 3), participants did not take full advantage of adaptive behaviours even though they were thermally uncomfortable. Therefore, in order to more explicitly evaluate the effectiveness of adaptive behaviours on thermal comfort, the experimental set-up is modified to promote the usage of adaptive behaviours: for example, desk fans are switched on and cool mats are put on all chairs at the beginning of the experiments in the study. However, they are allowed to turn off desk fans and remove cool mats at any time during the experiment.
Two adaptation options are specified, no adaptations (none) and all adaptations allowed (all). A total of five scenarios took place, namely 28°C (none), 28°C (all), 29°C (all), 30°C (all) and 31°C (all). An important point to note is that the data of the four scenarios, namely 28°C (all), 29°C (all), 30°C (all) and 31°C (all), are divided into two categories: ‘Overall’ and ‘Actor’. The former counts in all the participants in the experiment, whereas in the latter only those participants who exercised all the specified adaptive behaviours taken into consideration (namely persons taking all actions). These behaviours are desk fan usage, clothing adjustment, having cold water and cool mat usage. Other adaptive behaviours, similar to the dynamic study, were seldom exercised or their applications could not be detected. Additionally, only those who continuously drank cold water with a total amount of over 200ml/h, as well as those who kept their desk fan switched on, will be counted in the ‘Actor’ data. The planned number of participants for each experiment is 20, but a small number of individuals who signed up for the experiments did not show up due to personal issues.

Since few studies in previous literature focused on the benefits of having a cold drink while other adaptive behaviours are relatively better understood, two separate experiments were arranged to the exclusively evaluate the effectiveness of having cold water (cw). The two experiments, 29°C (ncw) and 29°C (cw), operated at the temperature of 29°C, where ‘ncw’ denotes that participants do not have any cold water and ‘cw’ denotes they do. The participants in both experiments were asked to wear T-Shirts and thin long trousers in order to control clothing variables. Additionally, they did not put on the long-sleeved shirts for the purpose of imitating an actual office situation in summer.

Different from the dynamic study, the duration of each experiment in this study is one hour during which participants were asked to fill in the corresponding part of a questionnaire every 10 minutes. Figure 4.2.7 illustrates the experimental progress for the scenario of 28°C (none). The questionnaire used for static temperature experiments, shown in Appendix 4.2, consists of seven parts, including the Initial Stage and Stage 1 to 6, with the identical questions as those in the dynamic study questionnaire. In order to neglect the effects of previous thermal
experiences, the answers for the Initial Stage, Stage 1 and Stage 2 are just used for reference. Regarding the percentage of desk fan usage, some participants switched off desk fans at some stages of the experiments, and this is regarded as the partial usage of desk fans. Table 4.2.2 summarise the features of the eight experiments included in this study.

![Figure 4.2.7. Illustration of the experimental progress of the scenario of 28°C (none).](image)

**Table 4.2.2. Summary of features of experiments.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Dynamic study</th>
<th>Static temperature study</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participants</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>Temperature</td>
<td>24-32°C</td>
<td>28°C</td>
</tr>
<tr>
<td>Adaptive behaviours allowed</td>
<td>All allowed</td>
<td>None</td>
</tr>
</tbody>
</table>

### 4.3 Dynamic study results and analysis

Table 4.3.1 summarises the results of the dynamic study’s questionnaires. In general, as temperature rises, more participants tend to exercise adaptive behaviours. It is worth noting that no participant was observed to put on the shirt again after taking off them. According to the percentage of participants using each adaptive behaviour, the preference for these adaptive behaviours are ranked as below:
Clothing adjustment > Desk fan usage > Having cold water > Cool mat> wet wipe

Body posture adjustment and activity variation are not counted since no obvious usage of these two adaptive behaviours has been detected. An important point to note is that most participants shortened sleeves or unbuttoned shirts instead of directly removing the shirt. In some cases, participants cast very high TSVs but still tended not to use desk fans, cool mats or even take off shirts. This is likely to be a result of cognitive tolerance introduced in Baker and Standeven (1996): people may be tolerant of a hot environment once they know the experiment is about to end. In terms of the fact that few participants used cool mats, it may partially attribute to the fact that cool mats were located at an inconvenient place for them to grab. Hence, it is important to make adaptive opportunities easily accessible to occupants.

Table 4.3.1 Dynamic study results.

<table>
<thead>
<tr>
<th></th>
<th>Beginning</th>
<th>26°C</th>
<th>28°C</th>
<th>30°C</th>
<th>32°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participants</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Percentage acceptability</td>
<td>76.19%</td>
<td>84.21%</td>
<td>61.90%</td>
<td>31.80%</td>
<td>19.05%</td>
</tr>
<tr>
<td>Average TSV</td>
<td>0.18</td>
<td>0.34</td>
<td>0.61</td>
<td>1.27</td>
<td>1.79</td>
</tr>
<tr>
<td>Average PMV</td>
<td>-0.16</td>
<td>0.30</td>
<td>0.87</td>
<td>1.47</td>
<td>2.17</td>
</tr>
<tr>
<td>Percentage of clothing taken off</td>
<td>-</td>
<td>5.26%</td>
<td>15.79%</td>
<td>47.37%</td>
<td>15.79%</td>
</tr>
<tr>
<td>Percentage of fan usage*</td>
<td>-</td>
<td>5.26%</td>
<td>10.52%</td>
<td>21.05%</td>
<td>57.89%</td>
</tr>
<tr>
<td>Percentage of having cold water</td>
<td>-</td>
<td>5.26%</td>
<td>21.05%</td>
<td>31.58%</td>
<td>21.05%</td>
</tr>
<tr>
<td>Percentage of cool mat usage</td>
<td>-</td>
<td>0%</td>
<td>0%</td>
<td>5.26%</td>
<td>5.26%</td>
</tr>
<tr>
<td>Percentage of wet wipe usage</td>
<td>-</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>5.26%</td>
</tr>
</tbody>
</table>

* The percentage of an adaptive behaviour usage denotes the percentage of experiment participants who exercise this adaptive behaviour.
Figure 4.3.1 illustrates box plots for all the PMV and TSV data. It indicates that average PMV values are less fluctuating than TSV ones. According to Table 4.3.1, the average TSV compare well with the average PMV at 26°C, but they begin to differentiate from each other remarkably from 28°C onwards. Six possible reasons for this phenomenon are listed below:

1) The effect of anticipated control: although adaptive behaviours are not exercised, the availability of these adaptive behaviours may relieve one’s thermal stress.
2) The effectiveness of these adaptive behaviours may be underestimated: the effectiveness of these adaptive behaviours are mainly derived from previous literature, but some adaptive behaviours may have more significant effectiveness in this case.
3) The PMV model underestimates the participants’ tolerance of high temperature: the PMV model is based on European citizens, while the experiment participants have adapted to the climate of Beijing which has a warmer summer than most European countries’. Hence, experiment participants may have more positive thermal sensations than what the PMV model suggests.
4) The effect of past thermal experience: due to the fact that the experiment was carried out in a dynamic environment, participants’ thermal sensations may be affected by the previous temperature. Hence, it is doubtful that whether the equilibrium between participants’ human body and the external environment has been achieved (or physiologically adapted) at the time that participants were filling in the questionnaires.
5) The effects of other adaptive behaviours may actually exist: although no obvious body posture adjustment or activity variation has been detected during the experiments, the effects of these adaptive behaviours may actually exist.
6) The limitations of the PMV model at high air temperature scenarios: the PMV model was found to be most accurate within the effective temperature range from 26 °C to 30 °C according to the study of Doherty and Arens (1988). Hence, due to the possible inherent limitations of the PMV model, it may not be suitable for scenarios with high air temperature over 30 °C. However, the discrepancy between average PMV and average TSV can also be detected at the temperature of 28 °C and 30 °C, so the possible inherent
limitations of the PMV model may not be the predominant cause of the discrepancy.

Figure 4.3.1. Box plots of PMVs and TSVs at each temperature.

4.4 Static temperature study results and analysis

Table 4.4.1 summarises the results of the static temperature study’s questionnaires. Similar to the dynamic study, the discrepancy between average PMV and average TSV still exists for the scenarios of 29°C (all), 30°C (all) and 31°C (all). However, comparable average PMV and average TSV can be found in the scenarios of 28°C (none), indicating the failure of the fifth speculation in the previous section. In other words, body posture adjustment and activity variation seem to play negligible roles in improving participants’ thermal comfort. The average TSV of 28°C (all) are very close to zero which causes significant uncertainty for the comparison between average PMV and average TSV as the neutral condition is more likely to be a range instead of a single point (Humphreys and Nicol, 2002). Box plots of the PMVs and TSVs at each scenario of the static temperature study are shown in Figure 4.4.1.
Table 4.4.1 Static temperature study results.

<table>
<thead>
<tr>
<th></th>
<th>28°C (none)</th>
<th>28°C (all) Overall/Actor</th>
<th>29°C (all) Overall/Actor</th>
<th>30°C (all) Overall/Actor</th>
<th>31°C (all) Overall/Actor</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participants</td>
<td>14</td>
<td>21/2</td>
<td>18/10</td>
<td>29/15</td>
<td>18/17</td>
</tr>
<tr>
<td>Percentage acceptability</td>
<td>35.7%</td>
<td>95.2%/100%</td>
<td>94.4%/100%</td>
<td>82.1%/80%</td>
<td>50%/47.06%</td>
</tr>
<tr>
<td>Average TSV</td>
<td>1.08</td>
<td>0.06/0</td>
<td>0.16/0.08</td>
<td>0.42/0.32</td>
<td>0.87/0.85</td>
</tr>
<tr>
<td>Average PMV</td>
<td>1.07</td>
<td>0.44/-0.36</td>
<td>0.42/0.19</td>
<td>0.94/0.73</td>
<td>1.30/1.28</td>
</tr>
<tr>
<td>Percentage of clothing taken off</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Percentage of desk fan usage (partial usage)</td>
<td>-</td>
<td>47.62% (33.33%)</td>
<td>77.78% (72.22%)</td>
<td>96.6% (82.1%)</td>
<td>94.4% (94.4%)</td>
</tr>
<tr>
<td>Percentage having cold water (≥200 ml/h)</td>
<td>-</td>
<td>28.57%</td>
<td>77.78%</td>
<td>51.72%</td>
<td>94.4%</td>
</tr>
<tr>
<td>Percentage of cool mat usage</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Percentage of wet wipe usage</td>
<td>-</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
4.4.1 Effectiveness of having cold water

One of the speculations for the deviation between PMV and TSV is underestimating the effectiveness of adaptive behaviours. The results of the two experiments, 29°C (ncw) and 29°C (cw), seem to support this justification.

As shown in Table 4.4.2, the 29°C (cw) data is subdivided into the ‘Overall’ and the ‘those who had no less than 200 ml/h’. The former includes all the participants in the scenario, whereas the latter looks at those who had the relatively larger amount of cold water (no less than 200 ml/h) in order to demonstrate the effectiveness of having cold water more clearly. Figure 4.4.2 illustrates the box plots for both 29°C (ncw) and 29°C (cw), and there are two outliers in the data of 29°C (ncw). Table 4.4.3 demonstrates the results of one-way ANOVA analysis, through the SPSS program, of these two sets of data, and the significance (namely the p-value) of 0.008.
suggests the high distinction between these two sets of data.

Compared with the 29°C (ncw) data, the 29°C (cw) data have a considerably larger percentage acceptability value and a much lower average TSV. Regarding the 29°C (cw) data, the ‘Overall’ data has a relatively smaller percentage acceptability value (75.0% against 87.5%) and slightly higher average TSV (0.43 against 0.40) than the data for those who had no less than 200 ml/h. Quantitatively analysis of the benefits of having cold water via adaptive increment is conducted in Section 5.1.

**Table 4.4.2. Comparison between the 29°C (ncw) and 29°C (cw) data.**

<table>
<thead>
<tr>
<th></th>
<th>29°C (ncw)</th>
<th>29°C (cw) Overall/ those who had no less than 200 ml/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participants</td>
<td>17</td>
<td>20 / 16</td>
</tr>
<tr>
<td>Percentage acceptability</td>
<td>58.8%</td>
<td>75.0% / 87.5%</td>
</tr>
<tr>
<td>Average TSV</td>
<td>0.97</td>
<td>0.43 / 0.40</td>
</tr>
<tr>
<td>Average PMV</td>
<td>1.05</td>
<td>0.78/0.71</td>
</tr>
<tr>
<td>Average amount of cold water taken per hour</td>
<td>N/A</td>
<td>261 ml/h / 314.38 ml/h</td>
</tr>
</tbody>
</table>
4.4.2 Effectiveness of anticipated control

In order to evaluate the effectiveness of anticipated control, the thermal comfort levels of those who did not exercise any adaptive behaviours at 28°C in the dynamic study (i.e. 28°C (dynamic study; none)) are compared with those in the scenario of 28°C (none). As a result, the former has a much larger percentage acceptability value as well as a considerably smaller average TSV than the latter (i.e. 54.55% against 35.70%, 0.63 against 1.08 as shown in Table 4.4.4), indicating that the anticipated control plays a remarkable role in relieving one’s thermal stress. The reduction of 0.45 in average TSV is consistent with the study of Zhou et al. (2014) which suggests a difference of 0.4-0.5 in TSV between the subjects with and without the control over the room’s temperature. This conclusion is supported by the analysis that the

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Table 4.4.3. One-way ANOVA analysis (excluding outliers shown in Figure 4.4.2).

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>2.844</td>
<td>1</td>
<td>2.844</td>
<td>8.084</td>
<td>0.008</td>
</tr>
<tr>
<td>Within Groups</td>
<td>11.609</td>
<td>33</td>
<td>0.352</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>14.453</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 4.4.2. Box plots for both 29°C (ncw) and 29°C (cw) Overall.
data of 28°C (dynamic study) and 28°C (dynamic study; none) compare well with each other in the percentage acceptability and average TSV values.

Table 4.4.4 Comparison between 28°C (dynamic study) and 28°C (none) data.

<table>
<thead>
<tr>
<th></th>
<th>28°C (dynamic study)</th>
<th>28°C (dynamic study; none)</th>
<th>28°C (none)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participants</td>
<td>19</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>Percentage acceptability</td>
<td>61.90%</td>
<td>54.55%</td>
<td>35.70%</td>
</tr>
<tr>
<td>Average TSV</td>
<td>0.61</td>
<td>0.63</td>
<td>1.08</td>
</tr>
<tr>
<td>Average PMV</td>
<td>0.87</td>
<td>1.05</td>
<td>1.07</td>
</tr>
</tbody>
</table>

4.4.3 Effects of past thermal experience

In the static temperature study, only the last four stages’ questionnaire answers were considered for the purpose of neglecting the effects of previous thermal experiences since empirically it takes about 30 minutes for a human body, when subjected to a new thermal environment, to reach heat balance. In this section, the questionnaire answers of all the stages are evaluated to find out the turning point from which onwards participants would have relatively stable thermal sensations. In order to limit the effects of adaptive behaviours, it only evaluates the scenarios of 28°C (none) and 29°C (ncw).

Figure 4.4.3 and Figure 4.4.4 illustrate the box plots of the average TSV of each stage for the scenarios of 28°C (none) and 29°C (ncw) respectively, and Table 4.4.5 lists the TSVs of each stage for these two scenarios. According to Table 4.4.4, for both scenarios, only the values of initial stages differ remarkably from other values whereas the values of other stages compare well with each other, indicating that participants perhaps had adapted to the environments within ten minutes. This may also apply to the dynamic study, so it is reasonable to believe that at the time participants were filling in the questionnaire, they have, to a great extent, acclimated to the environment, indicating the effects of past thermal experience could be minor. This justification is plausible as no participant were found to be sweating as a result of doing strenuous exercise before the experiment and the experiments were taken in
September when the external thermal condition was close to that of the climate chamber.

Figure 4.4.3. Box plots for the TSV data of each stage for 28°C (none).

Figure 4.4.4. Box plots for the TSV data of each stage for 29°C (ncw).
Table 4.4.5. Average TSV of each stage of 28°C (none) and 29°C (ncw).

<table>
<thead>
<tr>
<th></th>
<th>Initial Stage</th>
<th>Stage One</th>
<th>Stage Two</th>
<th>Stage Three</th>
<th>Stage Four</th>
<th>Stage Five</th>
<th>Stage Six</th>
</tr>
</thead>
<tbody>
<tr>
<td>28°C (none)</td>
<td>1.40</td>
<td>1.22</td>
<td>0.99</td>
<td>0.99</td>
<td>1.20</td>
<td>0.94</td>
<td>1.19</td>
</tr>
<tr>
<td>29°C (ncw)</td>
<td>1.35</td>
<td>0.97</td>
<td>0.98</td>
<td>1.05</td>
<td>0.95</td>
<td>0.93</td>
<td>0.94</td>
</tr>
</tbody>
</table>

4.4.4 Effects of participants’ tolerance of high temperature

Tolerance of high temperature, as a result of acclimatisation, is a physiological adaptation describing the reduced strain caused by the exposure to thermal stimuli as a consequence of the modifications of physiological reactions (de Dear et al., 1997). Since the experiment participants have acclimated to the hot summer of Beijing, they may have improved tolerance of high temperature, but the results of this study do not seem to support this.

By plotting the TSV-APD correlation, which links each scenario’s average TSV with actual percentage dissatisfaction values (APD) (calculated as 100% minus the percentage satisfaction value), against the PMV-PPD model, as shown in Figure 4.4.5, it suggests that APD is always higher than PPD. This means that participants are less satisfied with the thermal environment than what the PMV-PPD model suggests.

Hence, the participants’ tolerance of high temperature Line 7 - is APD and PPD a good metric for heat tolerance? Has this been used in previous literature/studies? in this study does not seem to be greater than those European subjects used for the derivation of the PMV-PPD model, and this is in contradiction to the third speculation. mentioned in the results and analysis of the dynamic study. More efforts need to be done to evaluate if the form of questions for the acceptability vote, which is much more complicated than the traditionally either-or question (namely either acceptable or unacceptable), Line 19 -PPD is calculated via an equation derived from PMV (Fanger, 1970). This same equation could be applied to calculate APD if all equation inputs are accounted for has something to do with the results. Additionally, the physiological adaptations include tolerance of high temperature may merely appear in extreme conditions which are beyond the scope of the thermal environment used in this study, and this will be discussed in detail in Section 5.3.
4.5 Discussion

4.5.1 Quantification of adaptive behaviours

According to the analysis in Section 4, among the six Speculation mentioned in the dynamic study, Speculation 1 and 2 may be the cause of the discrepancy between average PMV and average TSV. Namely, the discrepancy is mainly caused by anticipated control and underestimating the effectiveness of adaptive behaviours, in particular, having a cold drink. Hence, if the effect of anticipated control is eliminated and the effectiveness of adaptive behaviours is accurately reflected, the PMV model is believed to be capable of accurately representing participants’ average TSV in this case.

This is supported by the results that comparable PMVs and TSVs found in experiments of 28°C (none) and 29°C (ncw) in which no adaptive behaviour or anticipated control is involved. This argument is in accordance with the study of de Dear et al. (1997): Figure 4.3 in de Dear et al. (1997) show a perfect match between comfort temperatures of the adaptive model derived
for HVAC buildings and those obtained from ‘the adaptive PMV’. The latter ones were derived by using each building’s mean air speed, relative humidity, clothing level and metabolic rate as the inputs for the PMV model, and then iterating the operative temperature input until PMV = 0. Despite the fact that some other researchers obtained quite opposing results, de Dear et al. (1997) attributed this perfect match to the quality controls and precautions when dealing with the database.

Additionally, when validating the PMV model, it is necessary to take consideration of the valid range of PMV input parameter as suggested by Humphreys and Nicol (2002) and ISO (2005), not to mention the precision of the inputs for the PMV model. Also, the PMV model should be used cautiously in the regions with high relative humidity since local citizens have adapted to the high relative humidity conditions and therefore may not be very sensitive to the humidity levels. (Givoni et al., 2004; Nejad and van Meeteren, 2008).

Hence, it is believed that the mechanism of the PMV model can successfully apply to the TSVs obtained from experiments, and in turn allows the usage of TSVs to derive adaptive increments. For instance, with regard to the scenarios of 29°C (ncw) and 29°C (cw) (excluding those who had less than 200 ml/h of cold water), the difference between the neural temperatures of the two scenarios can be considered as the adaptive increment of having a cold drink.

Neutral temperatures can be estimated by iterating the operative temperature until PMV becomes zero by setting the corresponding TSV as the initial PMV value. The operative temperature at which PMV turns into zero is thought to be the estimated neutral temperature. By applying this method, results are shown in Table 4.5.1.

For 29°C (ncw) and 29°C (cw) (excluding those who had less than 200 ml/h cold water), the difference in estimated neutral temperature is 1.5 °C, which is much higher than the values given by Baker and Standeven (1996), Oseland et al. (1998) and Haldi and Robinson (2008) as
shown in Table 4.2.1, while experimental participants had similar amount of cold water (314.38 ml/h, as shown in Table 4.4.1) compared with 330 ml/h in the study of Baker and Standeven (1996). A possible reason for this may be that the cold water was kept cold with ice in this study, making it remain at a low temperature.

For 29°C (ncw) and 28°C (none), the only difference in adaptive behaviour usage is that participants in the former did not put on long-sleeve shirts. The difference in estimated neutral temperature of 1.9 °C compares well with the value (1.7 °C) from previous literature as shown in Table 4.2.1, in light of the fact that participants in the 28°C (none) study have slightly higher clo values.

It is important to note that estimated neutral temperatures derived from scenarios of 30°C (all) (Actor) and 31°C (all) (Actor) compare well with each other, indicating the neutral temperature to be over 29°C when all the adaptive behaviours are exercised. For this reason, the estimated neutral temperature derived from 29°C (all) (Actor) is an outlier and therefore is neglected. Hence, the adaptive increment for the ‘Actor’ data is about 4.7°C, where 4.7 °C is the difference between 24.8 °C (the estimated neutral temperature of 28°C (none)) and 29.5°C (the average value of the estimated neutral temperatures of 30°C (all) (Actor) and 31°C (all) (Actor)).

<table>
<thead>
<tr>
<th></th>
<th>29°C (ncw)</th>
<th>29°C (cw) Excluding those who had less than 200 ml/h</th>
<th>28°C (none)</th>
<th>29°C (all) Actor</th>
<th>30°C (all) Actor</th>
<th>31°C (all) Actor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average TSV</td>
<td>0.97</td>
<td>0.40</td>
<td>1.08</td>
<td>0.08</td>
<td>0.32</td>
<td>0.85</td>
</tr>
<tr>
<td>Estimated neutral temp.</td>
<td>26.7°C</td>
<td>28.2°C</td>
<td>24.8°C</td>
<td>28.9°C</td>
<td>29.4°C</td>
<td>29.6°C</td>
</tr>
</tbody>
</table>

The overall adaptive increment obtained from the above analysis may be validated by
reviewing the scenarios of 26°C (dynamic study; none) and 30°C (all) (Actor). The scenario of 26°C (dynamic study; none) denotes the 26°C scenario in the dynamic study with only those participants who do not exercise any adaptive behaviours taken into consideration. These two scenarios have almost the identical percentage acceptability values and average TSVs, whereas it has been specified above that the participants in the scenario of 26°C (dynamic study; none) enjoyed the benefits of anticipated control. This means that the actual neural temperature differences between these two scenarios should be a bit larger than 4°C. Table 4.5.2 below shows the comparison between these two scenarios and Figure 4.5.1 illustrates the box plots for these two scenarios.

Table 4.5.2. Comparison between the scenarios of 26°C (dynamic study; none) and 30°C (all) (Actor).

<table>
<thead>
<tr>
<th></th>
<th>26°C (dynamic study; none)</th>
<th>30°C (all) (Actor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of participants</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Percentage acceptability</td>
<td>86.67%</td>
<td>80%</td>
</tr>
<tr>
<td>Average TSV</td>
<td>0.30</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Figure 4.5.1. Box plots for TSVs of the scenarios of 26°C (dynamic study; none) and 30°C (all) (Actor).
However, a theoretically overall adaptive increment of 5.3°C should be obtained by adding up individual adaptive increments induced by corresponding adaptive behaviours: +1.5°C (having cold water), +1.9°C (clothing adjustment), +0.5°C (using cool mat) (estimated by using the SET* model based on the change in clothing level of 0.08 clo), + 1.4°C (desk fan usage). The possible reasons for the discrepancy between the theoretical and actual overall adaptive increments are discussed in detail in Chapter 3. A correction factor of 0.89 is obtained here and this is a result of some positive and negative factors. Positive factors include that the participants were provided with abundant adaptive opportunities without constraints which contribute to perceived control and the participants probably acclimated to warm environment as the experiments took place in hot summer. Negative factors may be that the artificial environment of the climate chamber may adversely affect the participants’ psychological adaptations and the benefit of exercising one adaptive behaviour is highly possible inhibited by another.

4.5.2 Individual differences, upper thermally comfortable temperature and preferences for adaptive behaviours

No obvious relationship was found between average TSV and each of the following factor, age, gender, BMI and air quality. Small sample size, as well as Insignificant differences in age and BMI among participants, may partially explain this.

At 30°C, by exercising adaptive behaviours, a majority of people still feel thermally comfortable under the experimental conditions, not to mention that people can access other adaptive behaviours such as ceiling fan usage, window opening and blind operation in practice. Hence, if many adaptive behaviours are allowed and properly exercised, people would find it thermally comfortable at an air temperature of 30°C or even higher. According to the percentage of adaptive behaviours being used in both the dynamic study and the static temperature study, some adaptive behaviours, such as body posture adjustment, wet wipe usage, activity variation and cool mat, are seldom exercised, whereas clothing adjustment, fan
usage, having cold water, cool mat usage are four adaptive behaviours frequently exercised by experiment participants.

Peoples’ preferences for adaptive behaviours may be dependent on ease of use, the effectiveness of the choice and economic concerns (Hwang et al., 2009). Occupants probably prefer the most convenient controls as opposed to the logically most effective controls (Leaman, 1999). An example from this study is that cool mat usage is a quite effective adaptive behaviour but was seldom exercised since cool mats cannot easily access by experiment participants. Additionally, people are not willing to sacrifice their thermal comfort to save energy in the workplace (Hwang et al., 2009), but economic concerns seem to play a crucial role in residences (Feriadi and Wong, 2004). Hence, office users would probably choose their preferred adaptive options based on the ease of use principle, but uncertainty could be very high. The uncertainty may be even higher for some partially unconscious adaptive behaviours like posture adjustment and activity level.

Generally, window opening, fan operation, clothing adjustment and having a cold drink are the four most frequently exercised adaptive behaviours in naturally ventilated buildings, but the ranking of these adaptive behaviours differs among various field studies. Some field studies found environmental adjustments (window opening and fan operation) are the most often exercised options (Wong et al., 2002), whereas other field studies found clothing adjustment as the most popular (Wei et al., 2010; Liu et al., 2012b). These discrepancies may be a result of the differences in the studied time of year and climate, and is more likely caused by constraints of adaptive options. For example, rain and outside noise may affect window operations, and a strict dress code may influence clothing adjustment. Hence, to model occupants’ adaptive behaviours using the above model, close attention should be paid to constraints over the adaptive behaviours.

4.5.3 Limitations of this study

1. To further validate the obtained results, it is necessary to increase the example size, and
simultaneously arrange more sets of experiments to separately evaluate more adaptive behaviours. In that case, more robust adaptive increments with standard deviation may be obtained.

2. Due to the unfamiliar context of climate chamber and the fact that the participants were being monitored, they might not feel free to adjust body postures as what they do in practice.

3. The activity level in this study is very low (this may partially explain why activity variation cannot be detected), but people perhaps have higher metabolic rates in real office environments. Hence, the results should be to some extent modified before putting into practice.

4. This study did not explicitly evaluate activity variation and therefore neglecting the argument that one’s metabolic rate may vary with the ambient environment or his/her thermal sensation (Baker and Standeven, 1996; Fanger and Toftum, 2002; Luo et al., 2016). Further studies need to be conducted to measure metabolic rate in an expert way, such as oxygen consumption measurement, and evaluate how it may be affected by adaptive behaviours.

4.6 Summary
This study shows that over 80% of the participants can still find it thermally acceptable at an operative temperature of 30°C on the condition that adequate adaptive opportunities are provided. The temperature is perhaps even higher in a naturally ventilated environment with easily accessible windows, more powerful desk fans, free dress code, etc. This study has found the adaptive increment of taking cold water to be 1.5°C which is more significant than previous literature suggest. The obtained actual overall adaptive increment is 4.7°C, smaller than 5.3°C which is the sum of individual adaptive increments of four most effective adaptive behaviours found in this study (i.e. clothing adjustment, desk fan usage, having cold water and cool mat usage), indicating a correction factor of 0.89. The interactions among these adaptive behaviours have been analysed and to some extent explain the discrepancy between the actual adaptive increment and the sum of individual ones. In contrast, other adaptive
behaviours, including body posture adjustment, activity variations, wet wipe usage and having a snooze, either had limited effectiveness or were seldom exercised.

Although behavioural adaptations are very effective in improving one’s thermal comfort, people may not fully take advantage of those available adaptive behaviours. In practice, it requires guidance, such as informing occupants the effectiveness of the adaptive behaviours, to take full advantage of adaptive behaviours. It is also vital that the adaptive opportunities are easy to use. Apart from behavioural adaptations, this study also demonstrates that means of psychological adaptation, namely anticipated control, plays an important role. Hence, the setpoint of an AC system can increase considerably when effective and easy-to-use adaptive behaviours are available, leading to a significant cut in AC energy consumption.
Chapter 5 - Field studies on adaptive thermal comfort in mixed mode offices

5.1. Introduction of this chapter

The studies in previous chapters have theoretically and experimentally evaluated adaptive thermal comfort. The lab experiments were conducted in a confined space without windows and failed to evaluate the psychological and physical influences of the natural environment on thermal comfort and other adaptive opportunities. Hence, it is necessary to conduct field studies to study adaptive thermal comfort in more detail. Before the field studies took place, a survey on adaptive opportunities in offices of East China was conducted, aiming to evaluate the range and availability of adaptive opportunities and how occupants perceive these adaptive opportunities. This survey was also used to provide some realistic guidelines to the field studies. It was conducted in the form of an online questionnaire which was created by using Wenjuanxing, a widely used online questionnaire system in China. The link to the questionnaire was sent to personal WeChats (a widely used social app in China) or WeChat groups of targeting subjects, and a total of 131 completed questionnaires were received. All the respondents are from Shanghai Municipality or Zhejiang Province, both of which belong to East China, enjoying a hot-summer and cold-winter climate. As shown in Appendix 5.1, a total of 13 questions are included in the questionnaire. The first question is about the type of office that subjects use, and questions 2-9 concern the available adaptive opportunities in offices. Questions 10-12 evaluate office users’ perceptions and habits with regard to window operations and the last question analyses the perceived effectiveness of 12 adaptive opportunities in thermal comfort improvement.

This chapter also includes the field studies conducted in the city of Ningbo in East China which aimed to provide practical guidelines to the adaptive thermal comfort studied in the theoretical and laboratory studies, and to analyse how office users exercise adaptive behaviours in practice. Thermal comfort levels and behaviours of four participants are studied in detail via monitors, surveys and interviews. A total of 497 completed thermal comfort
questionnaires were received and all the four participants were interview individually. The stochastic models of using AC, windows, desk fans and cool mats have been developed to find out the issues associated with the adaptive opportunities and how the availability of other adaptive behaviours affects the use of AC and windows. It is worth noting the field studies were not used for the robust validation of the alternative method of predicting adaptive thermal comfort which requires a much larger example size.

5.2 Results analysis and discussion of the survey on adaptive opportunities in offices of East China

5.2.1 The survey results analysis

Results show that the types of surveyed offices are evenly distributed with the smallest number of 25 for two-person private offices and the largest number of 43 for open plan offices. The numbers of one-person private offices and multi-person private offices are 28 and 35 respectively. 38.93% of respondents can ‘easily’ manually operate windows, and a comparable percentage (32.06%) of them can ‘relatively easily’ operate windows. The respondents who find it ‘relatively difficult’, ‘difficult’ and are ‘unable’ to operate windows are much fewer, accounting for 14.50%, 8.40% and 6.11% respectively. All the surveyed offices are provided with AC systems, among which central AC systems take up just over two-thirds. This, along with the high availability of openable windows, indicates that most (93.89%) offices in the area are MM buildings. About one-fourth (24.43%) of respondents clearly know that mechanical ventilation (MV) systems are available in their offices. Just over half of them do not have MV systems in their offices, and the rest of them are uncertain about it.

Just over half (51.15%) of respondents can access to fans (including ceiling fans, desk fans and floor standing pedestal fans), but the availability of other adaptive opportunities are low. Only 14.50% of the surveyed office users can have access to cold water, and below one-fourth (22.90%) of them benefit from net (non-upholster) chairs or chairs with cool mats. Moreover, most respondents can freely adjust their clothes and only about one-fourth (25.19%) of them have strict dress codes. According to Question 11, when AC is on, 17.56% of surveyed office
users often leave windows open, 67.18% sometimes leave windows open, and only 15.27% never leave windows open, indicating that office users are highly likely to ‘misuse’ windows with regard to temperature control. It is important to note that the use of windows is not just to control temperature but also air quality. Therefore, it may be perfectly appropriate to open a window even if the AC is on. As this study is mainly on thermal comfort studies, the term misuse of windows refers to the use of windows that adversely affects the indoor thermal environment.

The purposes of opening a window in summer and transitional seasons are both surveyed by using Question 10 and 12 respectively. Different from previous single choice questions, these two are ranking questions, although it is not necessary to rank all the options. Ranking number 1 denotes the most important purpose and the larger the number is, the less important the purpose is. The overall importance score of a purpose is calculated by using Equation 5.2.1 as follows (this method is embodied in the questionnaire system):

Importance score = (∑frequency*weight)/(the total number of respondents)

Equation 5.2.1

The weights of ranking numbers from 1 to 6 are from 6 to 1. For example, in terms of Question 10, a total of 65 people chose “Bringing in fresh air” as ranking number 1; 29 people chose ranking number 2; 8 people chose ranking number 3; 4 people chose ranking number 4; 1 person chose ranking number 5; and 1 person chose ranking number 6. Hence, the importance score can be calculated as follows:

Importance score = (65*6+29*5+8*4+4*3+1*2+1*1)/131
=4.44 (out of a maximum of 6)

In Summer, the rankings from the most important purpose to the least important one are (with the importance score in bracket): 1. bringing in fresh air (4.44); 2. circulating air to
increase air movement (4.36); 3. getting rid of dust and bacteria (1.63); 4. allowing sunlight in (1.49); 5. bringing in cool air to cool down the room (1.36); 6. connecting to the outdoors (1.2).

In terms of transitional seasons, the rankings change to: 1. bringing in fresh air (4.64); 2. circulating air to increase air movement (4.34); 3. bringing in cool air to cool down the room (2.16); 4. allowing sunlight in (1.69); 5. getting rid of dust and bacteria (1.4); 6. Connecting to the outdoors (1.06).

The last question is also a ranking question, surveying the perceived most effective means of improving thermal comfort. The effectiveness scores are also calculated using the Equation 5.1 above, but the maximum score changes to 12 in this case. The rankings from the perceived most effective means to the least effective one are (with the effectiveness score in bracket): 1. air conditioning system (10.73); 2. fan (6.54); 3. opening window (6.07); 4. wearing thin clothes (4.74); 5. operating curtain to prevent sunshine (4.33); 6. using cool mats (2.95); 7. drinking cold water; 8. moving to a cooler space (2.11); 9. using wet wipe (1.85); 10. having a siesta (1.6); 11. slowing down body movement (1.56); 12. posture adjustments (1.23).

5.2.2 Discussion on the survey results

85.72% of respondents in one-person private offices can easily or relatively easily access windows. This value decreases to 62.86%-68.00% for two-person private, multi-person private and open plan offices. The respondents who can easily operate windows will also be more likely to misuse windows: 23.5% of them often leave windows open when AC systems are on, while this value is only 13.7% for the other respondents (excluding those with windows that cannot be manually opened). This may be because occupants in one-person private offices can freely control windows, whereas the presence of other colleagues may socially reinforce “behaving energy efficiently” (Ackerly and Brager, 2013). According to the surveyed purposes of opening windows, people are highly likely to open windows for fresh air. This may be partially due to a lack of MV systems in delivering the perceived required air quality.

The respondents who can easily operate windows consider window opening a more important
means of improving thermal comfort (scoring 6.38 and ranking 3rd) than those who have difficulties in window operation (scoring 6.18 and ranking 4th) and those with unopenable windows (scoring 4.13 and ranking 7th). Occupants seem to be more familiar with the benefits of window use if they can easily operate windows and therefore occupants should be provided with easily accessible windows to enhance thermal comfort levels.

For both summer and transitional seasons, bringing in fresh air and circulating air to increase air movement are regarded as the two most important purposes of operating windows with comparable importance scores. This coincides with the argument that people couple the desire for fresh air with the desire for air movement although air movement essentially affects the physical thermal environment (Ackerly and Brager, 2013). Moreover, in fact, even recirculated moving air can considerably enhance perceived air quality (Aren et al. 2008). The importance score of “bringing in cool air to cool down the room” increases from 1.36 (ranking the 5th) for summer to 2.16 (ranking the 3rd) for transitional seasons, but the scores are still much lower than the ones relevant to fresh air and air movement. This is inconsistent with a survey conducted by Ackerly and Brager (2013) who argue that opening windows for cooling is of almost the same priority as it is for fresh air. This may be because local occupants highly rely on AC systems or fans for cooling as indicated by the results of Question 13 and some of them are unable to control windows as suggested by the results of Question 3. On the other hand, the survey of Ackerly and Brager (2013) was conducted on occupants in buildings with window signalling systems which effectively guide the occupants to rely more on window operations for cooling. Another reason may be that since window opening is the only means of getting fresh air in the majority surveyed offices, it may be an intrinsic perception of the occupants that opening a window is mainly for fresh air and therefore the purpose of using windows for fresh air is highly likely to overwhelm other purposes.

5.3 Methods of the field studies

Four occupants are involved in the field studies. All the four participants are close friends of the author so that the author could communicate with them efficiently and realise the
research goals smoothly. Although there are only a small number of participants involved in this study, this study aims to evaluate how adaptive behaviours improve individual thermal comfort and to explore how occupants exercise adaptive behaviours in practice. It is also easier to categorise the occupants and arrange follow-up interviews to better understand the obtained results. Occupant 1 is in a two-person private office, and during the field studies, her colleague in the same office was not often present. The other three occupants are situated in another building. Occupant 2 enjoys a one-person private office, and Occupants 3 and Occupant 4 share a two-person private office. Table 5.3.1 displays the basic information of the participants. Figure 5.3.1 and Figure 5.3.2 illustrate the buildings’ appearances and office layouts respectively. An important point to note is that all the offices are mixed mode offices where both AC systems and windows are manually controlled.

Table 5.3.1. Basic information about the four participants.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Office type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant 1</td>
<td>Female Two-person private office (office 1 in Building 1)</td>
</tr>
<tr>
<td>Occupant 2</td>
<td>Male One-person private office (office 2 in Building 2)</td>
</tr>
<tr>
<td>Occupant 3</td>
<td>Male Two-person private office (office 3 in Building 2)</td>
</tr>
<tr>
<td>Occupant 4</td>
<td>Male Two-person private office (office 3 in Building 2)</td>
</tr>
</tbody>
</table>

Figure 5.3.1. Appearances of Building 1 (left) and Building 2 (right).
5.3.1 A survey on the activeness of exercising adaptive opportunities

Before field studies took place and after the survey on adaptive opportunities in offices of East China was completed, another survey was firstly conducted to evaluate how often the field study participants would exercise adaptive opportunities. Previous literature provides some guidance on categorising the activeness of using adaptive opportunities: based on the frequency of exercising blind control or window operation, occupants are divided into active and passive users in the studies of Reinhart (2004) and Parys et al. (2011a), whereas active, average and passive users are defined in the study of Haldi and Robinson (2009). The differences in activeness may be caused by the ease of use, the occupants’ perceived effectiveness of and personal preferences of the adaptive behaviour, etc. The survey in this study contains a questionnaire, extending the use of activeness hierarchy for blind control and window operation to other adaptive behaviours, as shown in Appendix 5.2. Occupants were questioned how often they would exercise nine adaptive opportunities, namely AC operation, window operation, having a siesta, blind control, fan operation, using a cool mat, drinking cold water, clothing adjustment and using a wet wipe. There are four choices of the frequency, namely often, sometimes, rarely and never. The last question in the questionnaire requests the participants to rank the perceived importance of eight factors affecting overall comfort levels/working productivity, namely air quality, thermal conditions, acoustic conditions, visual conditions, air velocity, distractions from other occupants, humidity and office layout. Among the studied nine adaptive behaviours, AC operation, window operation, blind control and
having a siesta, a non-upholstered chair and a desk fan were readily available to Occupant 1, whereas only AC operation, window operation, blind control and having a siesta were accessible by Occupant 2, 3 and 4 before field studies took place. Only those adaptive behaviours claimed to be frequently used were selected for field studies in order to accurately reveal their effectiveness in improving thermal comfort. Apart from choosing appropriate adaptive behaviours for field studies, the survey also aims to explore possible means of practising adaptive opportunities more actively and correctly.

5.3.2 Field study setups

As mentioned above, field studies took place in three offices within two office buildings. The two office buildings are both high-rise buildings located in the city of Ningbo, which is a typical hot-summer and cold-winter city in East China. All the three offices are north-facing rooms on the 9th floor, so they are free from direct solar radiation and security issues. AC systems of all the three offices can be manually controlled, but none of the offices is equipped with an MV system. The field study period is from late July to early November in the year 2016 and divided into two phases. Phase 1 is the basic scenario from 26th July to 24th August, while additional adaptive opportunities are provided in Phase 2 which is from 25th August to 1st November, as illustrated in Table 5.3.2. Based on the results of the survey on the activeness of exercising adaptive opportunities (which will be discussed in detail in Section 5.4.1), using desk fans and cool mats are chosen as the additional adaptive opportunities. The desk fans and cool mats provided to Occupants 2, 3 and 4 are the same ones used in the lab experiments in Chapter 4. The desk fan used by Occupant 1 is similar to others’. The non-upholstered chair used by Occupant 1 and upholstered chairs used by other are shown in Figure 5.3.3. The laboratory study in Chapter 4 shows that using desk fans along with using cool mats will lead to an aggregated adaptive increment of 1.9°C, but this adaptive increment may be compromised by other available adaptive opportunities. For example, opening windows would increase air movement which may dampen the benefit of desk fan usage. Also, the participants were claimed to be average users of using desk fans. Hence, during the Phase 2 of the field studies, Occupants 2, 3 and 4 are asked to increase AC setpoint by only 1 °C (AC setpoints can only be
integers).

Figure 5.3.3. Non-upholstered (left) and upholstered (right) chairs

Table 5.3.2. Details about the two phases of the field studies.

<table>
<thead>
<tr>
<th>Phase number</th>
<th>No additional adaptive opportunities</th>
<th>Additional adaptive opportunities provided</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Period</td>
<td>26th July – 24th August</td>
<td>25th August – 1st November</td>
</tr>
</tbody>
</table>

Environmental conditions, including indoor air temperature, indoor relative humidity, window open/close status and outdoor temperature hourly data, were continuously monitored. Indoor air temperature and indoor relative humidity were recorded every 10 minutes by using Elitech RC-4HC temperature and humidity data loggers. TJHYKJ CKJM-1 magnetic switch data loggers are adopted to record window open/close status every minute. The data loggers are illustrated in Figure 5.3.4 and the specifications of the temperature/humidity data loggers are displayed in Table 5.3.3. The window status data loggers have already been successfully applied in previous literature (Shi and Zhao, 2016; Wei et al., 2016). Outdoor hourly air temperature data of the nearest meteorological station were obtained through a paid source available at: https://www.meteoblue.com/en/historyplus.
Figure 5.3.4. Illustrations of Elitech RC-4HC temperature and humidity data logger (left) and TJHYKJ CKJM-1 magnetic switch data logger (right).

Table 5.3.3. Specifications of Elitech RC-4HC temperature and humidity data logger.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature measuring range</td>
<td>-30°C ~ +60°C;</td>
</tr>
<tr>
<td>Temperature resolution</td>
<td>0.1°C</td>
</tr>
<tr>
<td>Temperature accuracy</td>
<td>±0.5°C</td>
</tr>
<tr>
<td>Humidity measuring range:</td>
<td>0 ~ 99 %RH</td>
</tr>
<tr>
<td>Humidity resolution</td>
<td>0.1 %RH</td>
</tr>
<tr>
<td>Humidity accuracy</td>
<td>±3 %RH</td>
</tr>
<tr>
<td>Record capacity</td>
<td>16000 points</td>
</tr>
<tr>
<td>Record interval</td>
<td>10s ~ 24 hours adjustable</td>
</tr>
</tbody>
</table>

A thermal comfort questionnaire is sent to each participant’s computers four times every weekday at 9.30, 11.00, 14.30 and 16.00. The thermal comfort questionnaire for the scenario without additional adaptive opportunities (shown in Appendix 5.3) collects information including name, clothing level, thermal sensation, thermal preference, etc., and the one for the scenario with additional adaptive opportunities (shown in Appendix 5.4) adds questions regarding additional adaptive opportunities. An important point to note is that clothing level is calculated based on an online self-determined clothing database available at http://web.arch.usyd.edu.au/~rdedear/clot.html.
5.3.3 Follow-up interviews

The field study participants were interviewed after field studies finished to deeper understand their behaviours and building performances. There are three general questions the participants were asked: 1) “Does using the desk fan and cool mat make you feel cooler so that you are willing to increase the AC system setpoint”; 2) “Are you willing to further increase AC setpoint when the desk fan and cool mat are available”; 3) “Please state the issues associated with the adaptive opportunities”. Other findings of the interviews will also be discussed in the following sections.

5.4. Field Study results analysis

5.4.1 The results of the survey on the activeness of exercising adaptive opportunities

The results of the survey are shown in Table 5.4.1. Among the studied nine adaptive behaviours, none of the respondents chose “never” to any adaptive behaviour. Hence, for each adaptive behaviour, the participants with the choice of “often”, “sometimes” and “rarely” are categorised as active users, average users and passive users respectively.

According to Table 5.4.1, all the participants are active users of AC operation. Except for Occupant 3 whose seat is far away from the window as shown in Figure 5.3.2, the rests are all active users of window operation, blind control and having a siesta. As for the other five adaptive behaviours unavailable in the offices, the participants are either active or average users of fan operation, using cool mats and clothing adjustment, whereas at least half of them are passive users of drinking cold water and using wet wipes. Possible reasons for this are that wet wipe may be used only in extreme conditions and the participants may not familiar with the effectiveness of having cold water or don’t have the habit of having cold water. In order to accurately reveal the effectiveness of adaptive behaviours in improving thermal comfort, using a wet wipe and drinking cold water, which are expected to be rarely exercised, are not included the additional adaptive opportunities provided in field studies. Moreover, during AC periods, low clothing levels (around 0.5 clo) of the participants were observed so that clothing adjustment may hardly attain further improvements in thermal comfort. Hence, clothing
adjustment is also excluded from the additional adaptive opportunities.

The last question in the questionnaire looks at the perceived importance of factors on overall comfort levels/working productivity. It is a ranking question, and the results are evaluated by using the Equation 5.1.1. Rankings of the factors are as follows with importance scores in brackets:

1. air quality (6.25);
2. thermal conditions (5.75);
3. acoustic conditions (5.50);
4. visual conditions (5.00);
5. air velocity (4.00);
6. Distractions from other occupants (2.50);
7. humidity (2.50);
8. office layout (0.75).

It shows that the participants have high requirements for both air quality and thermal comfort but the desire for fresh air is stronger than that for thermal comfort.

Table 5.4.1. Results of the survey on the activeness of exercising adaptive opportunities.

<table>
<thead>
<tr>
<th>Occupant 1</th>
<th>AC operation</th>
<th>Window operation</th>
<th>Blind control</th>
<th>Having a siesta</th>
<th>Fan operation</th>
<th>Using cool mate</th>
<th>Drinking cold water</th>
<th>Clothing adjustment</th>
<th>Using wet wipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Often</td>
<td>Often</td>
<td>Often</td>
<td>Often</td>
<td>SOMETIMES</td>
<td>Often</td>
<td>Rarely</td>
<td>Sometimes</td>
<td>Rarely</td>
<td></td>
</tr>
<tr>
<td>Occupant 2</td>
<td>Often</td>
<td>Often</td>
<td>Often</td>
<td>SOMETIMES</td>
<td>Often</td>
<td>Rarely</td>
<td>Often</td>
<td>Rarely</td>
<td></td>
</tr>
<tr>
<td>Often</td>
<td>Rarely</td>
<td>Rarely</td>
<td>Rarely</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>Rarely</td>
<td></td>
</tr>
<tr>
<td>Occupant 3</td>
<td>Often</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>Rarely</td>
<td></td>
</tr>
<tr>
<td>Occupant 4</td>
<td>Often</td>
<td>Often</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>SOMETIMES</td>
<td>Rarely</td>
<td></td>
</tr>
</tbody>
</table>

5.4.2 Field study results

A total of 497 completed thermal comfort questionnaires were received, counting on averagely about two responses per workday per person during the whole field study period.
Since diurnal changes in clothing level were seldom observed, the effectiveness of clothing adjustment is not evaluated in this study. Although all the participants often had siestas, how it may affect thermal comfort is out of the scope of this study.

Since a desk fan and a non-upholstered chair were already available to Occupant 1 before field studies took place, it only evaluates how the adaptive opportunities affect thermal comfort levels of Occupants 2, 3 and 4 at increased AC system setpoints. Additionally, based on logistic regression models introduced in Nicole (2001), it develops relationships between the probability of exercising the adaptive opportunities (AC, windows, desk fans and cool mats) and indoor/outdoor air temperatures. The results can be used to investigate how the participants exercise the adaptive behaviours in practice and explore possible modifications to these behaviours to achieve energy conservation and thermal comfort improvements. Since the use of AC largely affects indoor temperature, the relationship between AC operation and outdoor air temperature is evaluated. As fan operation and cool mat usage have little effect on indoor temperatures, the relationships between them and indoor air temperatures are developed. There is a disagreement on whether indoor or outdoor temperatures should be used to modelling window operations, so in this study, the relationship between window operation and both indoor and outdoor air temperatures are developed. The next section firstly evaluates the thermal comfort at increased AC setpoints, followed by the studies on the adaptive opportunities separately and the analysis on misuses of windows and AC systems.

### 5.4.2.1 Thermal comfort evaluation at increased AC system setpoint

Two periods, Period 1 and Period 2, from 1st August to 24th August and from 25th August to 9th September respectively, are chosen from Phase 1 and Phase 2 respectively for comparisons. Most of the days in the chosen periods have a daily highest temperature of from 30°C to 35°C. An exception is 7th September which suffered a sudden temperature decrease and therefore is excluded. Period 1 and 2 have similar reported clothing levels and comparable outdoor thermal conditions as shown in Figure 5.4.1 and Table 5.4.2.
Box plots of indoor temperatures for Period 1 and 2 of both Office 2 and 3 are illustrated in Figure 5.4.2, and the detailed comparisons of temperatures and thermal comfort criteria are shown in Table 5.4.3. The participants are considered thermally comfortable if they chose “Comfortable” in Question 5 of the thermal comfort Questionnaire without additional adaptive opportunities. Question 6 looks at the thermal preference of the participants. Thermal sensation values are calculated based on the ASHRAE seven-point thermal sensation criterion as discussed in Chapter 4.

As shown in Table 5.4.3, the average monitored indoor temperatures for Period 2 are about 1°C higher than those for Period 1 in both offices, but the thermal comfort levels for Period 2 remain at the same as or even slightly more positive than those for Period 1.
Table 5.4.2. Comparisons of outdoor air temperatures for Period 1 and 2.

<table>
<thead>
<tr>
<th></th>
<th>Period 1</th>
<th>Period 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>30.47</td>
<td>30.47</td>
</tr>
<tr>
<td>Median</td>
<td>30.48</td>
<td>30.41</td>
</tr>
<tr>
<td>Minimum</td>
<td>26.24</td>
<td>26.84</td>
</tr>
<tr>
<td>Maximum</td>
<td>34.77</td>
<td>33.59</td>
</tr>
<tr>
<td>Variance</td>
<td>4.78</td>
<td>2.77</td>
</tr>
</tbody>
</table>

Figure 5.4.2. Box plots of indoor air temperatures of Office 2 (left) and Office 3 (right) for Period 1 and 2.
Table 5.4.3. Comparisons of indoor air temperatures of Office 2 (left) and Office 3 (right) for Period 1 and 2.

<table>
<thead>
<tr>
<th>Indoor temperature analysis</th>
<th>Office 2</th>
<th>Office 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period 1</td>
<td>Period 2</td>
</tr>
<tr>
<td>Average</td>
<td>27.30</td>
<td>28.28</td>
</tr>
<tr>
<td>Median</td>
<td>27.30</td>
<td>28.20</td>
</tr>
<tr>
<td>Minimum</td>
<td>25.50</td>
<td>26.50</td>
</tr>
<tr>
<td>Maximum</td>
<td>29.50</td>
<td>30.60</td>
</tr>
<tr>
<td>Variance</td>
<td>0.99</td>
<td>0.45</td>
</tr>
<tr>
<td>Average thermal sensation</td>
<td>0.15</td>
<td>0.03</td>
</tr>
<tr>
<td>Thermal comfort percentage</td>
<td>86.3%</td>
<td>97.5%</td>
</tr>
<tr>
<td>Thermal acceptance</td>
<td>86.3%</td>
<td>97.5%</td>
</tr>
</tbody>
</table>

5.4.2.2 AC operation analysis

Since AC operations are not continuously monitored during field studies, the participants’ reported AC operations reflected in thermal comfort questionnaires are used. As all the participants claimed to be active AC users, all the data are aggregated. The proportion of AC being turned on as a function of outdoor air temperature for both Phase 1 and 2 are derived as shown in Equation 5.4.1 and 5.4.2 respectively. A simple linear function is used for Phase 1 as it only covers a short temperature spectrum, whereas a logistic function is applied for Phase 2. The functions are illustrated in Figure 5.4.3, along with binned survey results (2°C intervals). Outdoor air temperature instead of indoor air temperature is chosen for this analysis, because AC indoor air temperature is largely influenced by AC usage and not independent of the actions of turning on/off AC.

Statistically strong relationships between AC operation and outdoor air temperature ($R^2=0.892/0.936$) have been found. As can be seen from Figure 5.4.3, AC is much more frequently used in Phase 1 than that in Phase 2. The additional adaptive opportunities may be the main reason that reduces AC usage and it perhaps also due to the seasonal effect on AC.
usage (i.e. occupants may rely less on AC for cooling in other seasons than in summer even if outdoor temperatures are similar). In Phase 2, although the participants are provided with abundant adaptive opportunities, ACs will still be turned on for about 30% of the time at an outdoor temperature of 26 °C which is favourable for natural ventilation as a means of cooling.

$$p_{AC} = 0.02x + 0.32 \quad R^2 = 0.892 \quad \text{Equation 5.4.1}$$

$$\text{Logit}(p_{AC}) = \log \frac{p_{AC}}{1-p_{AC}} = 0.37 \times T_{out} - 10.57 \quad R^2 = 0.94 \quad \text{Equation 5.4.2}$$

![Figure 5.4.3. Reported and fitted proportion of AC on in relation to outdoor air temperature.](image)

The logistic curve for Phase 2 is also compared with the ones obtained by Chen et al. (2014) for Taiwan and by Rajil et al. (2008a) for Europe and Pakistan, as shown in Figure 5.4.4. All the curves are derived from the data of mixed mode building where fans are available. The curve of this study is similar to the ones in Rajil et al. (2008a) but differs significantly from the one of Chen et al. (2014). The curve of Chen et al. (2014) indicates AC will not be used until outdoor temperature rises above 30°C. This is mainly due to the application of a fee-for-service AC (i.e. occupants need to pay for AC usage) but Chen et al. (2014) still found high thermal comfort levels.
Figure 5.4.4. Comparisons among different studies of the proportion of AC on.

5.4.2.3 Window operation analysis

As discussed in Section 5.2, there are various purposes of opening windows. Among them, the desire for fresh air, air movement and cooling are the top three intentions. However, it is very difficult to modelling window operations for fresh air and air movement and therefore few existing models consider the factors (Parys et al., 2011a). During the periods when AC systems were frequently used, results show that windows were also often used. Follow-up interviews indicate that the reason for this is that the participants always complained about the air quality when AC was being turned on. Hence, for AC periods in this study, window operation is highly likely not for thermal comfort purposes. The period from 15th September onwards, when there are fewer observations of AC use, is chosen for window operation analysis.

By using logistic analysis, window open probability functions involved with both indoor and outdoor temperatures are derived. All the participants claimed to be active window users except for Occupant 3, but Occupant 4 in the same office with Occupant 3 would probably actively take control of the window. Hence, all the window operation data are aggregated. The proportion of time when the window is open as a function of indoor and outdoor air temperature are derived based on logistic regression as shown in Equation 5.4.3 and 5.4.4 respectively.
It has been found that the proportion of window open is statistically strongly correlated with both indoor and outdoor air temperature ($R^2=0.87/0.85$). This could be explained by the argument that it may be the indoor temperature that triggers window opening actions with thermal comfort purposes, but it is perhaps the outdoor temperature that determines the opening duration (Rijal et al., 2008b). The functions are plotted in Figure 5.4.5 and Figure 5.4.6, along with binned monitored results (1°C intervals).

$$\text{Logit} (p_{\text{win}}) = \log \frac{p_{\text{win}}}{1-p_{\text{win}}} = 0.37 \times T_{\text{in}} - 9.79 \quad R^2 = 0.87 \quad \text{Equation 5.4.3}$$

$$\text{Logit} (p_{\text{win}}) = \log \frac{p_{\text{win}}}{1-p_{\text{win}}} = 0.28 \times T_{\text{out}} - 7.02 \quad R^2 = 0.85 \quad \text{Equation 5.4.4}$$

![Figure 5.4.5. Monitored and fitted proportion of AC on in relation to indoor air temperature](image-url)
Figure 5.4.6. Monitored and fitted proportion of AC on in relation to outdoor air temperature.

The obtained curves are then compared with other studies, as shown in Figure 5.4.7 and Figure 5.4.8. As for the curves involved with indoor air/operative temperatures, the one obtained in this study compares well with the ones derived for the UK (Nicol and Humphreys, 2004), Europe (Nicol and Humphreys, 2004) and Switzerland (Haidi and Robinson, 2009). A higher proportion of window usage is found in this study when compared with the one for Pakistan (Nicol and Humphreys, 2004) which has a similar climate to the city where this study took place. This may be because the participants in this study are all active window users. Another reason may be that although the occupants in this study may use window less frequently for cooling down the room than Europeans, they may open windows more often for fresh air and air movement.

As for the curves involved with outdoor air temperatures, the one obtained in this study is more sensitive to outdoor temperatures. A very low window opening frequency is found at low outdoor air temperatures in this study. This may be because the participants have more concerns about cold feelings than poor air quality which needs further clarifications. An important point to note is that the curve based on the Beijing climate (Wei et al., 2015) (Beijing
is also in the hot-summer and cold-winter zone of China) implies low window opening frequency at high temperatures which may be caused by severe outdoor air pollution.

Figure 5.4.7. Comparisons among different studies on the proportion of window open in relation to indoor temperatures.

Figure 5.4.8. Comparisons among different studies of the proportion of window open in relation to outdoor temperatures.
5.4.2.4 Desk fan operation analysis

The proportion of desk fan being turned on as a function of indoor air temperature is derived based on logistic regression as shown in Equation 5.4.5. Since fan operations are not continuously monitored, the participants’ reported desk fan usage reflected in the thermal comfort questionnaires are used for the derivation. As all the participants claimed to be average fan users as discussed in Section 5.4.1, all the data in Phase 2 are aggregated. A logistic curve of the proportion of using desk fan based on Equation 5 is plotted in Figure 5.4.9, along with binned survey results (1°C intervals). This curve is compared with the ones obtained by Rijal et al. (2008a) and Chen et al. (2014), as shown in Figure 5.4.10.

\[
\text{Logit} (p_{\text{fan}}) = \log \frac{p_{\text{fan}}}{1-p_{\text{fan}}} = 0.53 \times T_{\text{in}} - 15.45 \quad R^2 = 0.92
\]

Equation 5.4.5

The curve of this study follows a similar trend as other studies, but it indicates that fan usage found in this study is generally less frequent than that in the studies of Rijal et al. (2008a) and Chen et al. (2014). The highest proportion of usage is only about 50% corresponding to the surveyed highest indoor temperature of 29°C. A possible reason is that occupants are just average users of fan operation and not all of them have formed the habit of using desk fans. There is no fan operation reported at the air temperatures of above 29°C, implying that the participants primarily tend to use AC systems for cooling at high indoor air temperatures.
Figure 5.4.9. Reported and fitted proportion of fan on in relation to indoor air temperature.

Figure 5.4.10. Comparisons among different studies on the proportion of fan on.

5.4.2.5 Cool mat usage analysis

To author’s knowledge, no logistic analysis on cool mat usage has ever been conducted and
this section attempts to derive the proportion of cool mat usage as a function of indoor temperature based on logistic regression. Indoor air temperature is of interest here as it is highly likely the trigger of using cool mats and would not be influenced by the actions. As discussed in Section 5.4.1, three of the participants are claimed to be active cool mat users and only one is an average user, so all the data in Phase 2 are aggregated. Equation 5.4.6 shows the derived function which is also plotted in Figure 5.4.11, along with the binned survey results (1°C intervals).

\[
\text{Logit } (p_{\text{cool mat}}) = \log \frac{p_{\text{cool mat}}}{1-p_{\text{cool mat}}} = 0.52 \times T_{\text{in}} - 13.06 \quad R^2 = 0.93 \quad \text{Equation 5.4.6}
\]

Using cool mats and indoor air temperature are found to be strongly correlated \((R^2=0.93)\). The probability of using cool mats approaches a hundred percent at temperatures over 30°C, whereas cool mats would rarely be used below 20°C.

![Figure 5.4.11. Reported and fitted proportion of using cool mat in relation to indoor air temperature.](image)

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5.4.2.6 Misuse of windows and AC systems

Common misuses of windows and AC systems include opening windows at a high external air temperature and simultaneously operations of windows and AC systems. Ackerly and Brager (2013) argue that the misuses may easily occur since occupants usually operate window to restore comfort instead of saving energy. In this study, the misuses may be primarily caused by the contradictory requirements for air quality and thermal comfort as well as the unawareness of environmental conditions.

The following misuses of windows and AC are discovered from the results of thermal comfort questionnaires and follow-up interviews: when AC is being turned on, windows are still open; there are still reported AC operations when outdoor temperatures are even below 24°C which is favourable for natural cooling; during AC period, participants sometimes will put on clothes when feeling cool instead of turning down or off AC; The participants would set a very low AC setpoint to quickly cool down the room at first arrival in the office.

5.5. Discussion on the field studies

When additional adaptive opportunities were provided, the participants can still feel thermally comfortable at an increased AC setpoint. According to the follow-up interviews, all the participants claimed that benefitting from using desk fans and cool mats, their offices were thermally comfortable at the increased AC setpoints and they were willing to further increase AC setpoints. Although further studies need to be conducted to evaluate whether further increases in AC setpoint are actually acceptable and how other adaptive opportunities (e.g. having cold water and clothing adjustment) can improve thermal comfort in practice, it has shown a good potential of saving cooling energy by using additional adaptive opportunities.

The proportion of window open has been found statistically strongly related to both indoor and outdoor air temperatures. However, windows were sometimes found open at high outdoor temperatures and when AC systems were operating. This probably results from the participants’ high air quality requirements and it may be resolved by installing MV systems or
to some extent relieved by night cooling. An important point to note that the windows of office 1 were always open and windows of the other two offices were always closed during the night. In the flow-up interview, Occupant 1 claimed that window opening during night was to ensure a good air quality level at the beginning of a day. The proportion of using desk fans and cool mats have also been found strongly correlated to indoor air temperatures. The frequency of desk fan operation was generally low while cool mats were frequently used at high indoor air temperatures.

Although effective adaptive opportunities were available, the participants still rely largely on AC to cool down the room. It has found a higher frequency of AC usage in this study than others especially compared with the study of Chen et al. (2014). In this study, an even higher frequency of AC usage was observed in Phase 1 when less adaptive behaviours were available. A possible reason for the frequent use of ACs is that the participants can easily operate AC systems without any energy concerns. It is also because they are free from social concerns as they are in either one-person or two-person private offices (one may behave more energy efficiently at the presence of other colleagues as argued by Ackerly and Brager (2013)). Additionally, once AC is on, indoor environment is separated from outside, making occupants unaware of whether outdoor air is favourable for cooling, which may increase AC operation duration.

Hence, it is necessary to guide occupants to become more active and effective in using adaptive behaviours and meanwhile limit AC usage. This can be achieved by providing abundant adaptive opportunities to occupants and educating them about the benefits of adaptive behaviours in thermal comfort improvement. This can be assisted by the instructions from building managers and more advanced mechanical systems, such as a window signalling system (Ackerly and Brager, 2013) and automatic window and AC controls. Automatic controls can react quickly and adequately to the changes in environmental conditions. However, occupants’ desires for comfort may vary and would prefer having controls over the building, so a balance between automatic and manual controls should be carefully designed. This issue
may be tackled by using an advanced mixed mode system which will be introduced in the next chapter. To improve occupants’ energy concerns would be another way of energy conservation. The study of Chen et al. (2014) provides an effective way of limiting AC usage by adopting fee-for-service AC systems without compromising thermal comfort.

This study also finds a limitation of AC operations that the thermal environment usually responds slowly to AC operations and changes in AC setpoints. This leads to the use of low AC setpoints to tackle high temperatures at the beginning of a day and the situation that participants sometimes will put on clothes when feeling cool instead of turning down or off AC. The first issue can be resolved by night cooling and promoting the use of more quickly responding adaptive opportunities, such as using fans and drinking cold water. The second issue may be tackled by using a window signalling system or automatic window and AC controls mentioned above.

The original AC setpoints are found to be 26°C or 27°C at which the participants would feel thermally comfortable. According to the theory behind the adaptive increment thermal comfort, the temperature may be resulted from a baseline thermal comfort temperature and adaptive increments of existing behavioural and psychological adaptations. The existing adaptive behaviour may include window operations, blind control, activity adjustment and posture adjustment. However, similar to the results of the lab experiment, activity adjustment and posture adjustment cannot be captured through the field studies and not consciously detected by the participants themselves according to the interview results. Hence, targeting studies should be conducted to validate the effectiveness of activity adjustment and posture adjustment. Despite activity adjustment and posture adjustment, the combined effects of window operations and blind control raise the baseline thermal comfort temperature to about 26°C or 27°C, in accordance with the theoretical studies presented in Chapter 3. The difference in AC setpoints supporting the argument that before applications, both adaptive increments and the baseline thermal comfort temperature should be examined by fully considering individual differences and local environmental conditions.
The recorded relative humidity is high, ranges from 58.3% to 84.4% for Phase 1 and from 44.5% to 89.0% for Phase 2. However, no relationship between thermal comfort level and relative humidity has been found, nor complaints about the high relative humidity. This is consistent with other studies that residents in a humid climate are likely to adapt to the humid environment and not sensitive to the changes in humidity conditions (Givoni et al., 2004; Nejad and van Meeteren, 2008; Wu, 2015).

5.6 Limitations of the field studies and future work
According to Section 5.3, although setpoint was asked to increase by 1°C, the average indoor temperature is less than 1°C higher. This may be due to the fact that occupants can freely control AC systems and they sometimes were not willing to sacrifice comfort to obey the instructions. Future field studies may be conducted where AC operations can be manipulated by a central controller to take over the manual control of AC operations for the analysis of the upper limit of thermal comfort temperature. Due to the limitations of field study conditions and the number of participants, only two adaptive opportunities have been analysed. The effectiveness of other adaptive behaviours should be evaluated in future field studies. Although there are only a small number of participants involved in this study, this study aims to evaluate how adaptive behaviours improve individual thermal comfort and to explore how occupants exercise adaptive behaviours in practice. It is also easier to categorise the occupants and the follow-up interviews help to better understand the obtained results.

The probability functions are derived based on active AC, window and cool mat users and average desk fan users and therefore should be applied carefully. More types of occupants should be analysed to expand the applications of the probability functions. The derived probability functions of AC usage, window operation, using desk fans and cooling mats should be further verified based on a larger example size. The probability functions should also be improved by including other factors that affect the use of the adaptive behaviours. Other possible factors comprise air quality, time of a day, active/passive user factor, ease of use
factor, the availability of other adaptive opportunities, etc. For example, as air quality has been found to be an essential factor affecting window operation, both indoor temperature and air quality may be regarded as variables to form a multi logit regression to predict the probability of window operation. Other examples include that operating a blind is highly related to solar radiation and have old drink may be largely affected by thirsty sensations.

5.7 Summary
Office users in East China rely largely on AC systems for cooling, and they use windows more frequently to get fresh air and air movement rather than cooling down the room, which may easily lead to misuses of windows and AC systems. Assuming that an MV system is available to deliver the required level of fresh air, occupants should be educated about the benefits of opening windows for cooling and guided to more frequently and correctly operate windows. Only 6.11% of survey respondents are not able to operate windows, indicating most offices in the area are equipped with openable windows. However, there is a low availability of other adaptive opportunities, including those experimentally proved to be effective in improving thermal comfort in Chapter 4: only about 50%, 20% and 14.5% of office users have access to fans, cool mats (or non-upholstered chairs) and cold water. Although some adaptive opportunities are very effective in improving thermal comfort, office users are unfamiliar with their effectiveness and may tend to use those familiar adaptive opportunities. For example, Chapter 4 has proved drinking cold water to be a very effective way of cooling, but it only ranks seventh in this survey. Hence, it is essential to provide and demonstrate the effectiveness of such available adaptive opportunities. Additionally, air movement should be encouraged which contributes directly to both thermal comfort and perceived air quality. The results obtained in this chapter provide some realistic guidelines to the field studies introduced in the next chapter.

Thermal comfort levels and behaviours of four participants are studied in detail via monitors, surveys and interviews. Results show that the thermal comfort temperature of occupants increases by at least 1°C when desk fans and cool mats are available. Statistically strongly
stochastic models of using AC, windows, desk fans and cool mats have been developed. It is worth noting that the stochastic model of cool mat usage is one of the first attempts to study cool mat usage in detail. These stochastic models assist to identify some issues associated with exercising adaptive opportunities in practice (e.g. low operation frequency of desk fans and misuses of windows and AC) and evaluate how the availability of other adaptive behaviours affects the use of AC and windows. However, the stochastic models should be carefully used in other studies as it requires further verifications with a larger number of participants involved. It also concludes that extra efforts are needed to promote the usage of adaptive opportunities and guide occupants to more frequently and correctly exercise them. According to Chen et al. (2014), the involvement of energy concerns will largely reduce AC usage without compromising thermal comfort, so it should be considered in the MM building designs to achieve better energy performances.

A thorough investigation on adaptive thermal comfort is conducted by using theoretical studies, lab experiments, surveys and field studies from Chapter 3 to 5. It also explores the highest operative temperature at which people may still feel thermally comfortable under the experimental conditions, as well as the preferences for various adaptive behaviours. In the next chapter, based on the above adaptive thermal comfort studies and the analysis of existing MM buildings, it proposes an MM system which encourages occupants to exercise adaptive opportunities and improves both comfort levels and energy efficiency. The performance of the proposed MM system is analysed by using building performance simulations which requires a user behaviour model. The Rijal’s algorithm (Rijal et al., 2008), a stochastic behaviour model embodied in ESP-r, is used to represent occupants’ adaptive behaviours. It is basically a window operation probability algorithm, but it can also model fan operations and takes into consideration the existence of other adaptive behaviours. Apart from its comprehensive feature, other reasons this model were chosen are that it is generated based on the climate of Pakistan which is similar to Shanghai’s climate and the probability functions of window and fan operations used in the Rijal’s algorithm compare well with the ones derived for East China as presented earlier in this chapter.
Chapter 6 – Proposing a mixed mode ventilation system and its performance analysis

6.1 Introduction of this chapter

Previous chapters mainly focus on the studies of occupants’ adaptive thermal comfort and the analysis of existing MM buildings. Based on the findings from the previous chapters, this chapter proposes an MM system which promotes the use of manually controlled windows and other adaptive opportunities. It also integrates automatic controls over an advanced window system, a signalling system and an associated HVAC system. In this chapter, a detailed description of the proposed MM system will be presented, followed by the performance studies on the system by using buildings performance simulations. A total of thirteen simulation scenarios with different levels of adaptive opportunities and various settings of the HVAC and advanced window systems are proposed. This chapter has also explored how the alternative method of predicting adaptive thermal comfort introduced in Chapter 3 and stochastic behaviour model may be used in building performance modelling.

6.2 Outline of the MM system

Misuses of windows, such as opening windows at a high external air temperature and simultaneously operations of windows and HVAC systems, were found in field studies and questionnaires. The misuses may be caused by the contradictory requirements for air quality and thermal comfort as well as the unawareness of environmental conditions. The misuses may easily occur since occupants usually operate windows to restore comfort instead of saving energy (Ackerly and Brager, 2013). Automatic controls over windows, on the other hand, can react quickly and properly to the changes in environmental conditions and status of the HVAC system. However, occupants’ desires for comfort may vary and would prefer having controls over the building, so the automatic controls alone may not perfectly satisfy the occupants. The proposed MM system aims to find a balance between the manual and automatic controls by using an advanced window system.
The advanced window system consists of an upper window and a lower window. The upper window is designed to be automatically controlled responding to environmental and system parameters, such as indoor temperatures, outdoor temperatures, external air pollution, wind velocity and the operation status of the AC system, etc. The lower window can be both manually and automatically controlled. The design of the lower and upper windows enables the stack effect which improves the air exchange between the indoor and outdoor and in turn promote energy conservation and thermal comfort. The design of the lower window can also limit the effects of the elevated air movement on the occupants by the window. A light shelf is installed between the upper and lower windows as the shading device. The purposes of using light shelves are not only to achieve an even daylight distribution, but also to avoid the issue that traditional shading devices, such as curtains, may block the paths for incoming outdoor fresh air. Additionally, it could also to some extent prevent the occupants from being distracted by the operations of the upper window.

A signalling system is also included in the MM system to guide occupants to operate windows correctly. It monitors indoor and outdoor environmental conditions and informs occupants whether the conditions are suitable for opening/closing windows. The signalling system in this study develops on the window signalling systems described in literature review to include the warning of severe outdoor conditions (e.g. air pollution, strong wind and heavy rain), containing three lights: 1) the green light indicates that windows should be opened; 2) the red light indicates that windows should be closed; 3) the blue light indicates severe outdoor conditions. Another important part of the MM system, the associated HVAC system, is carefully designed and triggered once window operations and other adaptive opportunities fail to meet fresh air or thermal comfort requirements.

6.3 Control strategies of the MM system

A centralised controller (can be part of a Building Management System (BMS) in practice) is used to systemically integrate the window automation system, the signalling system and the HVAC system. It processes the signals generated from a range of indoor and outdoor sensors
(internal air temperature sensors, external air temperature sensors, window status sensors, indoor CO₂ concentration sensors, occupancy sensors, a wind speed sensor and an outdoor pollution sensor) and actuates the signalling system, the automatic windows and the HVAC system to operate accordingly.

Occupants can freely control over the lower window of the advanced window system, whereas the upper window and the HVAC system is automatically controlled. In order to maximise thermal comfort, the centralised controller controls the HVAC system regardless of the operations of the lower window and rely on the signalling system to correct the misuses of the lower window. Hence, the MM system is a partial changeover system as the changeover is realised between the automatically controlled upper window and the HVAC system, but concurrent operations of the manually controlled lower window and the HVAC system would occasionally occur.

Setpoints are needed for the changeovers between window automation system and the AC system, and between the window automation and the MV system. As for the temperature setpoint used as the changeover between window automation system and the AC system, it can be determined using the alternative method of predicting adaptive thermal comfort. The baseline comfort temperature is estimated according to the field study in Chapter 5 and the adaptive increments are based on the study in Chapter 3 and Chapter 5. According to the field studies in Chapter 5, occupants are satisfied with the AC setpoint of 26°C when they can freely operate windows and this value can be elevated when other adaptive opportunities are available. Hence, the baseline temperature setpoint for the changeover between the window automation and the AC system is set to 26°C which is consistent with the one used by Henze and May-Ostendorp (2012). The overall adaptive increment is resulted from using fans and other adaptive behaviours (e.g. using cool mat and activity adjustment). A low correction factor is used as occupants are not familiar with the adaptive behaviours which may constrain the effectiveness of the adaptive behaviours. Hence, the overall adaptive increment is set to 2°C. An important point to note is that this section does not aim to test the alternative method
of predicting adaptive thermal comfort, the above process is shown here as an illustration. Moreover, a lower window opening setpoint is also required to prevent from bringing in cold air to cause discomfort. May-Ostendorp (2012) recommends this temperature to be 15°, under which the automatically controlled window will be kept shut down. An MV system works along with CO₂ sensors to maintain the indoor CO₂ concentration level at 900 ppm. This value is based on the suggested indoor CO₂ concentration level of 700 ppm above the outdoor (ASHRAE, 2013).

The MM system primarily aims to provide occupants with effective personal controls over their thermal environments to enhance physical and psychological adaptations which in turn will improve their thermal comfort levels. The associated HVAC system and automatically controlled windows assist occupants to improve comfort levels at a low cost at extreme thermal and air quality conditions. The control strategies of the automatic windows may be contradictory in achieving thermal comfort and good air quality, for example, windows are shut down to prevent the external hot air from coming in but meanwhile indoor air quality may be poor. In this case, the automatic windows operate primarily to meet thermal comfort requirements and the HVAC system will support to maintain air quality. Conflicts of thermal comfort and fresh air requirements may also occur in the control strategies of an HVAC system, in particular, an all-air system. Hence, the control strategies of each component of the MM system should be carefully elaborated to avoid malfunctions and a proposal of the control strategies are shown in Table 6.3.1.
Based on the time of day, the presence of occupants and external environmental conditions, etc., four operation modes of the MM system are elaborated, namely standard mode, standby mode, night cooling mode and pollution mode. In each mode, the control strategies of the HVAC system and window automation vary and are described in detail below.

**Standard mode:** This mode is for the situation that the controlled space is occupied. The upper window is automatically opened/kept open when the external air temperature falls below the setpoint and the external air temperature is lower than the internal. Otherwise, the upper window would be shut down/kept closed. The AC system is triggered once the indoor temperature goes above the setpoint under the condition that the upper window is closed. The MV system begins to operate once the indoor CO₂ concentration level goes above the setpoint of 900 ppm provided that both the lower or upper windows are closed. In other words, the opening status of either the lower or upper window will signal the centralised controller to shut down the MV system. In order to prevent the MV system being switched on/off too frequently, it allows an overrun of 100 ppm above the setpoint.

**Standby Mode:** This mode is activated when the room is unoccupied during working hours. In this mode, the maximum power output of both the AC and MV systems are reduced to the
minimum level. The conditions on which the AC system and MV system are operating remain unchanged, maintaining indoor air temperature and CO₂ concentration levels two degrees higher than the setpoints.

**Night cooling mode:** this mode is activated when the office is unoccupied during after-hours. In this mode, both the lower and upper windows will be automatically opened once the external air temperature falls below the setpoint and is lower than the internal. Night cooling is capable of cooling down the structure of the building and in turn reduces cooling loads during the daytime. The HVAC system can operate to maintain a high setpoint (30°C is suggested by Henze and May-Ostendorp (2012)) or can be disabled in this mode.

**Severe mode:** Once one or more severe outdoor conditions, including air pollution, strong wind and heavy rain, are detected, the automatic control system overrides the manual controls to shut down the upper and lower windows. If the office is occupied, the HVAC system is switched on to maintain the setpoint when necessary. However, the HVAC system can operate to maintain a high setpoint or can be disabled in this mode.

As presented in Table 6.3.1, the signalling system operates in parallel with the HVAC system and window automation and has three modes:

**Green light:** when the external air temperature falls below the setpoint and is lower than the internal, the green light is energised to indicate that windows should be opened (or kept open) to cool down the room.

**Red light:** when the internal air temperature is higher than the setpoint and the external temperature goes above the setpoint, the red light is energised to indicate that windows should be shut down (or kept closed).

**Blue light:** The blue light is energised when a severe outdoor condition occurs corresponding
to the severe mode of the HVAC system and it suggests exercising other adaptive opportunities other than window operations.

6.4 Simulation set-ups

6.4.1 The building model

The analysis tool used for simulations is the whole building simulation programme, ESP-r. A typical one-person private office, as shown in Figure 6.4.1, is chosen for studies. According to Ackerly and Brager (2013), occupants in open plan offices are more positively responded to signalling systems than those in private offices. This is because occupants in private office feel free to use windows, whereas ‘active’ window users or even building managers in open plan will take actions for others (Ackerly and Brager, 2013). Hence, more misuses may occur in private offices and therefore it requires more involvements of automatic systems and effective signalling systems.

![Figure 6.4.1. The office model used in ESP-r.](image)

This office, measuring at 3m*4m*3m height is part of an office building and only its south wall is exposed to the exterior. All spaces adjacent to the office are assumed to have similar
environmental conditions. It assumes that the occupant sits close to the operable window and therefore could easily operate the lower window. Its basic information and construction details are illustrated in Table 6.4.1. The climate of Shanghai, a typical city in the summer-hot and winter cold zone of China, is used for analysis. Table 6.4.2 shows the schedules and internal heat gain information. The assumed internal heat gain of the office, as shown in Table 6.4.2, are typical values suggested by CIBSE Guide A (2006). An important point to note is that temporary absence of the occupant during working hours is neglected and only the one-hour unoccupied lunch time is considered.

Table 6.4.1. Basic Information and construction details of the ESP-r model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Shanghai, China</td>
</tr>
<tr>
<td>Orientation</td>
<td>The external wall facing due south</td>
</tr>
<tr>
<td>Width, depth and floor to ceiling height</td>
<td>3 m, 4m and 3m</td>
</tr>
<tr>
<td>External wall (exterior insulation)</td>
<td>U value is 0.548</td>
</tr>
<tr>
<td>Windows</td>
<td>double glazed, U-value =2.8 W/m²K</td>
</tr>
<tr>
<td>Admittance</td>
<td>5.05 W/m²K</td>
</tr>
<tr>
<td></td>
<td>(High level of thermal mass)</td>
</tr>
</tbody>
</table>

Table 6.4.2. Schedules and internal heat gains for the occupant, light and equipment.

<table>
<thead>
<tr>
<th></th>
<th>Heat gain or heat gain Density</th>
<th>Schedules (weekdays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant</td>
<td>Sensible: 70W; Latent: 45W</td>
<td>9 am-12 am; 1 pm– 6 pm</td>
</tr>
<tr>
<td></td>
<td>(secretary type)</td>
<td></td>
</tr>
<tr>
<td>Light (Fluorescent-triphosphor)</td>
<td>9 W/m²</td>
<td>9 am – 6 pm</td>
</tr>
<tr>
<td>Equipment gain</td>
<td>15 W/m²</td>
<td>9 am – 6 pm</td>
</tr>
</tbody>
</table>

6.4.2 Window operation algorithm

The Rijal’s algorithm (Rijal et al., 2008), a stochastic behaviour model embodied in ESP-r, is used to represent occupants’ adaptive behaviours. It is basically a window operation probability algorithm, but it can also model fan operations and takes into consideration the existence of other adaptive behaviours. As it is generated based on the climate of Pakistan which is similar to Shanghai’s climate, the probability functions of window and fan operations used in the Rijal’s algorithm compare well with the ones derived from the field studies conducted in East China presented in Chapter 6. The comparisons between the probability
functions are illustrated in Table 6.4.3 below.

<table>
<thead>
<tr>
<th>The proportion of window open</th>
<th>The Rijal’s algorithm</th>
<th>Field studies by the author</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/(1+EXP(-0.525Tₐ*+14.9))</td>
<td>1/(1+EXP(-0.687Tₐ*+16.3))</td>
</tr>
<tr>
<td>The proportion of fan on</td>
<td>1/(1+EXP(-0.595Tₐ*+16.4))</td>
<td>1/(1+EXP(-0.527Tₐ+15.45))</td>
</tr>
</tbody>
</table>

*Tₛ and Tₑ denote indoor air temperature and indoor operative temperature respectively.

The Rijal’s algorithm regards the indoor operative temperature as the only stimuli to the actions of opening/switching on windows, fans and doors. Based on numerous field studies in Pakistan, logit functions are derived to calculate the probabilities of windows, fans and doors being opened/switched on at given indoor operative temperatures. The Rijal’s algorithm models opening and closing actions by using a “deadband”. A “deadband” is basically a comfort zone based on a comfort/neutral temperature. For example, a deadband of 4°C denotes a comfort zone of a comfort/neutral temperature ±2°C. The comfort temperature is determined using the adaptive model developed for Pakistan (i.e. it is linearly related to the running mean temperature). Rijal et al. (2008) argue that door operation is not strongly related to thermal concerns so deadbands are not applicable to door operations. When the indoor operative temperature goes above the comfort zone and the window status is closed, the probabilities of windows opening or fans switching on are compared to a randomly generated number to determine the actions on operating windows and fans. Similarly, closing actions for windows, fans and doors will take place when the indoor operative temperature falls below the occupant’s comfort zone.

Nicol and Humphreys (2007) suggest a basic comfort zone of 4K, which can be enlarged by exercising adaptive behaviours. An important point to note is that the Rijal’s algorithm considers the fact that fan usage will elevate comfort temperature and therefore the function for calculating comfort temperature will change once a fan is operating. The detailed working
principle of the Rijal’s algorithm integrated into ESP-r is presented in Appendix 6.1.

6.4.3 Details about the advanced window system

A schematic picture of the advanced window system is shown in Figure 6.4.2 The windows opening type is top-hung outward opening, whose advantage is that it can to some extent prevent rain from coming into the room. The dimension of the upper window is 1.5m*0.7m height. In order to prevent the incoming air from blowing away the paper on the desk and from disturbing the occupant, only the higher pane of the lower window is operable whose dimension is also 1.5m*0.7m height. The effective operable area is assumed to be 50% of the total area for simulations.

For a south facing facade, Place and Howard (1990) suggest that the exterior length of a light shelf ($L_{ext\_lightshelf}$) should be between 1.25 and 1.5 times the height of the upper window. According to Littlefair (1995), the external length ($L_{ext\_lightshelf}$) should be smaller than the difference between the height of the light shelf from the floor ($H_{lightshelf}$) and the working plane ($H_{workplane}$), and the interior length of a light shelf ($L_{int\_lightshelf}$) should be equal to the height of the upper window ($H_{upper\_win}$). Hence, lengths of exterior and interior light shelf are both designed to be 1m.
6.4.4 Details about the control strategies during simulations

As the discussed above there is a changeover between the HVAC system and the upper window. To determine the energy saving potential of the MM system, it is necessary to evaluate the energy performance of the HVAC system on the condition that the changeover is disabled. In that case, the AC system keeps running to maintain the temperature setpoint regardless of the external environmental conditions and window status. During simulations, it is achieved by using an ideal control over the AC system. On the other hand, as for the simulations of the changeover system, a relatively complete loop of the AC system is built up using the plant network module in ESP-r, as shown in Figure 6.4.3. in order to accurately simulate the complex control logic and discover any possible issues of this system in practice (e.g. issues associated with changeovers between different modes). The AC system is a Variable Air Volume (VAV) type, but, for simplicity, it neglects the details of supply air cooling processes (i.e. it directly adopts a supply air at 13°C in simulations) and mixing of the supply and return air. Also, due to frequent usage of either the HVAC system or windows, the air quality is assumed to be guaranteed for the most of time. For this reason, the fresh air supply

Figure 6.4.2. Schematic picture of the advanced window system.
The MM system, the volume flow rate of supply air in this study reacts to the external air temperature (i.e. it estimates cooling loads based on external temperature, but it could be imprecise). The volume flow rate is modulated from the minimum to the maximum value when the external temperature rises from the setpoint to the 0.5°C over the setpoint, as explained in Table 6.4.4. This control type is adopted due to the absence of suitable multi-task control laws in ESP-r, so this system mainly relies on the reheater in the VAV box to precisely maintain the indoor air setpoint which can be overall energy inefficient. However, this study focuses on the cooling energy consumptions and cooling loads of the office, while the AC system’s overall energy efficiency is not a big concern. In practice, a more energy-efficient AC system with more advanced control strategies should be used which will be discussed in detail in Section 6.6.

Figure 6.4.3. Schematic drawing of the simplified VAV AC system used for simulations.
Table 6.4.4. The control of volume flow rate of the VAV system.

<table>
<thead>
<tr>
<th>External air temperature</th>
<th>&lt; setpoint</th>
<th>≥ setpoint and ≤ setpoint+0.5°C</th>
<th>&gt; setpoint+0.5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume flow rate of AC</td>
<td>Minimum (background volume flow rate of 0.02 m3/s*)</td>
<td>Increase linearly from the minimum to the maximum</td>
<td>Maximum (calculated based on the cooling load of the office)</td>
</tr>
</tbody>
</table>

*zero flow rate within the plant is not allowed in ESP-r, so there is a minimum background volume flow rate leading to a background cooling load.

In order not to oversize the AC system, the maximum volume flow rate of the changeover system is calculated based on the simulation results of the non-changeover system which vary among different scenarios. The Equation 6.1 below is used for calculation:

\[ Q = C_p m \Delta T \]  

(Equation 6.1)

Where,

- \( Q \) is the peak cooling load in kW
- \( m \) is the mass flow rate of supply air in kg/s, which can be calculated by \( V \times \rho \), where \( V \) is the volume flow rate in m\(^3\)/s and \( \rho \) is air density which is about 1.18 kg/m\(^3\) at 25°C and 1 atm.
- \( C_p \) is the specific heat of air, which is about 1.005 kJ/(kg*K) at 25°C
- \( \Delta T \) is the temperature difference between the setpoint and the temperature of the supply air from the cooling coil in °C.

Since the non-changeover system adopts an ideal control, the peak cooling load of the office coincides with the maximum output of the cooling system. According to Table 6.5.1, the peak cooling load of the non-changeover system in the basic scenario, \( Q_0 \), is 1.80 kWh. The maximum volume flow rate of the changeover system, \( V_0 \), should be no less than the calculated volume flow rate to meet the peak cooling load:
\[ V_0 \geq V = \frac{Q_0}{(C_p \rho \Delta T)} \]

\[ = \frac{1.8 \text{ kWh}/(1.005\text{kJ}/(\text{kg}^\circ\text{C}) \times 1.18\text{kg/m}^3 \times (26^\circ\text{C} - 13^\circ\text{C}))}{0.118\text{m}^3/\text{s}} \]

Hence, a \( V_0 \) of 0.12 m\(^3\)/s is enough to meet the peak cooling load, and the maximum volume flow rates of the changeover system in other scenarios can be calculated in the same way.

### 6.4.5 Other operating details

It assumes that the conditions of air pollution, rainfall and wind speed are always acceptable. As discussed above, an MV system is excluded from the simulation and the air quality is assumed to be maintained at a good level. It also assumes that the door is kept closed, so only single-sided natural ventilation takes place. The air movement simulation is conducted by the airflow network module in ESP-r. Simulations are based on the meteorological dataset for Shanghai, available in the EnergyPlus climate database. A typical period of the transitional season, 45 days from 1\(^{st}\) September to 15 October, is chosen for simulation. Figure 6.4.4 illustrates the external air temperatures for the period from 15\(^{th}\) August to 31\(^{st}\) October, the majority of the chosen days enjoy a daily peak temperature of around 30°C and have considerable diurnal variation in temperature, which is suitable for the study of MM systems. The time-step of the simulations is set to 1 minute, which means that the performance would be simulated every 1 minute.

Since the Rijal’s algorithm is a stochastic model, five simulations are run for each case in which the Rijal’s algorithm is used to limit uncertainties. Also, a deadband of 0.5°C is assigned for AC operation (i.e. AC system will not be switched on until the indoor air temperature reaches 26.5°C and will be switched off when it falls below 25.5°C) in order to reduce the frequency of using AC system. The PID control law is used to maintain the temperature setpoints.
6.4.6 Scenarios for simulations

A total of 13 scenarios are elaborated and each scenario has different combinations of the following parameters: AC setpoint, the availability of the light shelf, window type, occupant behaviour model, the availability of a fan and other adaptive opportunities and the availability of night cooling. An important point to note is that as for window type, the traditional window denotes that the upper window of the advanced window system permanently remains closed. The details about the scenarios are illustrated in Table 6.4.5 below.

These scenarios aim to evaluate the effectiveness of following strategies in achieving energy conservation and thermal comfort improvement: the changeover between the AC system and the automatic window, using a fan and other adaptive opportunities, the advanced window system and the optimal control of the lower window, the light shelf and night cooling. The optimal control of the lower window is an ideal scenario that the occupants completely follow the instructions provided by the signalling system.

An important point to note is that it assumes that using a fan and other adaptive opportunities leads to an increase in comfort temperature of about 2°C which is reflected in the rise of AC setpoint from 26°C to 28°C. This increase can be realistically achieved according to the studies.
presented in Chapter 5. The Scenario 2 and 4 are two exceptions: they do not increase the AC setpoint and only analyse the effects of using a fan and other adaptive opportunities on window operation behaviours. Using a fan and other adaptive opportunities will also change the deadband of the window operation from 4°C to 8°C in the Rijal’s algorithm settings in ESP-r.

Table 6.4.5. Details of the thirteen scenarios studied.

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>AC setpoint (°C)</th>
<th>The availability of Light shelf</th>
<th>Window type</th>
<th>Occupant behaviour model on window operations</th>
<th>The availability of a fan and other adaptive opportunities</th>
<th>The availability of night cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Basic scenario)</td>
<td>26</td>
<td>NO</td>
<td>Traditional window</td>
<td>The Rijal’s Algorithm</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>1</td>
<td>26</td>
<td>YES</td>
<td>Traditional window</td>
<td>The Rijal’s Algorithm</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>YES</td>
<td>Traditional window</td>
<td>The Rijal’s Algorithm</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>YES</td>
<td>Advanced windows</td>
<td>The Rijal’s Algorithm</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>YES</td>
<td>Advanced windows</td>
<td>The Rijal’s Algorithm</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>YES</td>
<td>Traditional window</td>
<td>Optimal control</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>YES</td>
<td>Advanced windows</td>
<td>Optimal control</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>7</td>
<td>26</td>
<td>YES</td>
<td>Advanced windows</td>
<td>Optimal control</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>8</td>
<td>28</td>
<td>YES</td>
<td>Traditional window</td>
<td>The Rijal’s Algorithm</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>9</td>
<td>28</td>
<td>YES</td>
<td>Advanced windows</td>
<td>The Rijal’s Algorithm</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>YES</td>
<td>Traditional window</td>
<td>Optimal control</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>11</td>
<td>28</td>
<td>YES</td>
<td>Advanced windows</td>
<td>Optimal control</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>YES</td>
<td>Advanced windows</td>
<td>Optimal control</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
6.5 Results analysis

The results of the simulations are shown in Table 6.5.1 below. Eight parameters are used to evaluate the performances of the MM system, including the average daily cooling energy consumption of the controlled room without changeover, peak cooling load without changeover, average daily cooling energy consumption with changeover, peak cooling load with changeover, the percentage of room air temperature meeting the setpoints, the proportion of the lower window open, the proportion of the upper window open and the percentage of window misuse time. As mentioned above, five simulations are run for each scenario in which the Rijal’s algorithm is used as the occupant behaviour model. The fluctuations of the values are not significant and the largest value differs from the smallest value by less than 5% for the most of time, and the relevant values presented in Table 6.5.1 are average ones.

As mentioned above, a deadband of 1°C (±0.5°C of the setpoint) used for the temperature setpoint control. Nicol and Humphreys (2007) argue that occupants can tolerate small shifts (±1°C) from the comfort temperature. The tolerances may vary among different people. This study evaluates two levels of tolerance, namely high tolerance and low tolerance. The former corresponds to a strict setpoint criterion allowing the maximum of 0.5°C diverging from the setpoint, whereas the latter corresponds to a loose setpoint criterion only allowing the maximum of 1°C diverging from the setpoint. For simplicity, a letter “S” is used to denote scenario. For example, Scenario 0 is written as S0 for short. The effectiveness of the strategies used for energy conservation and thermal comfort improvement is evaluated separately as below.

6.5.1 The changeover between the AC system and the automatic window

The average daily cooling energy consumptions with and without changeover are both calculated for each scenario. In terms of one single scenario, the largest cooling energy consumption gap of 0.59 kWh between the systems with or without changeover occurs in S0, whereas the smallest gap of 0.05 kWh occurs in S12. Although the magnitude of gaps of the
later scenarios become smaller, they are still significant in terms of percentage difference. The percentage difference ranges from 12.1% occurring S3 to 37.2% occurring S8. However, in S7, the cooling energy consumption without changeover (0.69 kWh) is only slightly less than the one with changeover (0.70 kWh). This is probably due to the background cooling load for the system with changeover as discussed above.

However, the large cooling energy reductions are achieved at the expense of sacrificing thermal comfort. As for S0, only 56.0% and 67.4% of the working hours meet the strict and loose setpoint criteria respectively, although the values are improved with the presence of other strategies, which will be discussed in the later sections. Since the cooling energy consumptions of the room with and without changeover vary among different scenarios with a similar trend, the following analysis will only focus on how other strategies may affect the cooling energy consumption of the MM system with changeover.

6.5.2 The availability of a fan and other adaptive opportunities

The benefits of using a fan and other adaptive opportunities in comfort temperature elevation can be determined by evaluating five sets of comparison: S1 vs S8, S3 vs S9, S5 vs S10, S6 vs S11 and S7 vs S12. The increase of 2°C in AC setpoint results in a dramatic reduction in the average daily cooling energy consumption ranging from 0.47 kWh for S7 vs S12 to 1 kWh for S1 vs S8. The improvements on the percentage of indoor air temperature meeting the strict and loose setpoint criteria resulted from using a fan and other adaptive opportunities vary significantly, reducing from 6.2% for S3 vs S9 to 0.6% for S5 vs S10. As for the loose setpoint criterion, the improvements are 6.4% for S1 vs S8, 2.3% for S3 vs S9 and 4.7% for S5 vs S10. However, in terms of the comparisons of S6 vs S11 and S7 vs S12, the S6 and S7 have slightly higher values than S11 and S12. Hence, there is no consistent relationship between using a fan and other adaptive opportunities and the improvements on the percentage of indoor air temperature meeting setpoint criteria has been found, which can be explained by the fact that in each scenario the AC system is sized to just meet the corresponding peak cooling load.
On the other hand, the increase in AC setpoint significantly reduces the peak cooling loads. It reduces mostly significantly by 0.86 kW from 1.42 kW in S6 to 0.56 kW in S11, while the smallest reduction by 0.3 kW is found between 0.66 kW in S7 and 0.36 kW in S12. Due to the elevation in indoor air temperature, the lower window opens much more often but its misuse time reduces remarkably.

As discussed above, S2 and S4 are two exceptions, and the two sets of comparison of S1 vs S2 and S3 vs S4 merely aim to analyse the effects of using a fan and other adaptive opportunities on window operation behaviours. It considerably reduces the proportion of the lower window open and leads to a significant reduction in window misuse time which in turn slightly cut cooling energy consumption and increase the percentage of time meeting the setpoint criteria.

6.5.3 Advanced window system

There are four sets of comparisons, namely S1 vs S3, S5 vs S6, S8 vs S9 and S10 vs S11, can be used to evaluate the effectiveness of the advanced window system. It makes almost no difference to the peak cooling load and window misuse time. It only slightly cut cooling energy consumption and moderately reduces the lower window’s open time. On the other hand, it dramatically raises the percentage of time when the strict/loose setpoint criteria are met by 10.3%/12.1% for S1 vs S3, 8.3%/10.4% for S5 vs S6, 13.5%/8.6% for S8 vs S9 and 11.0%/5.3% for S10 vs S11.

6.5.4 Optimal control of the lower window

Four sets of comparisons, S1 vs S5, S3 vs S6, S8 vs S10 and S9 vs S11, can be used to analyse the advantages of the optimal control over manual controls of the lower windows. As can be expected, the optimal control eliminates all the misuses of windows and moderately increases the overall proportion of the lower window open except for S1 vs S5 in which the proportion slightly reduces. The optimal control of the lower window slightly reduces the peak cooling load by 0.07 kW and 0.09 kW for S1 vs S5 and S3 vs S6 respectively, whereas more significantly reduces the peak cooling load at the higher setpoint by 0.23 kW for S8 vs S10 and 0.43 kW for
S9 vs S11. The optimal control also contributes considerably to average daily cooling energy reductions ranging from 0.09 kWh for S8 vs S10 and 0.39 kWh for S1 vs S5. If the percentage of time meeting the strict/loose setpoint criteria is at a low level, the optimal control can slightly increase the percentage by about 3%-5% for S1 vs S5, S3 vs S6 and S8 vs S10. However, as for the high percentage of time meeting the strict/loose setpoint criteria for S9 vs S11, the optimal control plays a negligible role.

6.5.5 Light shelf

The only difference between S0 and S1 is that S1 adopts a light shelf. The light shelf prevents sunlight from coming in, leading to a decrease in indoor mean radiant temperature (MRT). The application of a light shelf slightly reduces the proportion of the lower window open from 70.4% to 67.0% but almost makes no change to window misuse time. Both the average daily cooling energy consumption and the peak cooling load drops considerably by 0.62 kWh and 0.38 kW respectively. Meanwhile, it moderately increases the percentage of time meeting the strict and loose setpoint criteria by 3.6% and 6.9%.

6.5.6 Night cooling

Night cooling is the only variable for the following two sets of comparisons, S6 vs S7 and S11 vs S12. It shows that night cooling can largely cut average daily cooling energy consumption by 0.43 kWh for S6 vs S7 at the lower AC setpoint and by 0.17 kWh for S11 vs S12 at the higher one. Night cooling is also capable of drastically lessening the peak cooling load by 0.76 kWh and 0.2 kWh for S6 vs S7 and S11 vs S12 respectively. Additionally, it can slightly increase the percentages of hours meeting the strict and loose setpoint criteria. The percentage for S7 is larger than the one for S6 by 8.3% and 2.8% in terms of strict and loose setpoint criteria respectively. While the differences between S11 and S12 reduces to 4.3% and 0.2% respectively.
Table 6.5.1. Details of the simulations results.

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>AC Setpoint (°C)</th>
<th>Average daily cooling energy consumption (no changeover) (kWh)</th>
<th>Peak cooling load (no changeover) (kWh)</th>
<th>Average daily cooling energy consumption (kWh)</th>
<th>Peak cooling load (kW)</th>
<th>% indoor air temp. meeting the strict/loose setpoint criteria</th>
<th>% Lower window open</th>
<th>% Upper window open</th>
<th>% window misuse time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Basic scenario)</td>
<td>26</td>
<td>2.77</td>
<td>1.80</td>
<td>2.18</td>
<td>1.88</td>
<td>56.0%/67.4%</td>
<td>70.4%</td>
<td>0.0%</td>
<td>17.9%</td>
</tr>
<tr>
<td>1</td>
<td>26</td>
<td>1.94</td>
<td>1.42</td>
<td>1.56</td>
<td>1.50</td>
<td>59.6%/74.3%</td>
<td>67.0%</td>
<td>0.0%</td>
<td>17.7%</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>1.93</td>
<td>1.41</td>
<td>1.48</td>
<td>1.49</td>
<td>57.4%/70.4%</td>
<td>56.1%</td>
<td>0.0%</td>
<td>10.3%</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>1.71</td>
<td>1.42</td>
<td>1.50</td>
<td>1.51</td>
<td>69.9%/86.4%</td>
<td>62.7%</td>
<td>66.9%</td>
<td>17.6%</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>1.66</td>
<td>1.42</td>
<td>1.42</td>
<td>1.50</td>
<td>67.8%/82.5%</td>
<td>57.4%</td>
<td>66.9%</td>
<td>13.4%</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>1.42</td>
<td>1.33</td>
<td>1.17</td>
<td>1.43</td>
<td>64.6%/79.1%</td>
<td>66.9%</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>1.24</td>
<td>1.32</td>
<td>1.12</td>
<td>1.42</td>
<td>72.9%/89.5%</td>
<td>66.9%</td>
<td>66.9%</td>
<td>0%</td>
</tr>
<tr>
<td>7</td>
<td>26</td>
<td>0.70</td>
<td>0.59</td>
<td>0.69</td>
<td>0.66</td>
<td>75.0%/91.9%</td>
<td>66.9%</td>
<td>66.9%</td>
<td>0%</td>
</tr>
<tr>
<td>8</td>
<td>28</td>
<td>0.89</td>
<td>1.00</td>
<td>0.56</td>
<td>1.01</td>
<td>62.6%/80.7%</td>
<td>82.4%</td>
<td>0.0%</td>
<td>9.5%</td>
</tr>
<tr>
<td>9</td>
<td>28</td>
<td>0.69</td>
<td>1.00</td>
<td>0.52</td>
<td>0.99</td>
<td>76.1%/88.7%</td>
<td>75.6%</td>
<td>87.2%</td>
<td>9.2%</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>0.64</td>
<td>0.87</td>
<td>0.47</td>
<td>0.78</td>
<td>65.2%/83.8%</td>
<td>87.2%</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>28</td>
<td>0.54</td>
<td>0.50</td>
<td>0.39</td>
<td>0.56</td>
<td>76.2%/89.1%</td>
<td>87.2%</td>
<td>87.2%</td>
<td>0%</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>0.27</td>
<td>0.32</td>
<td>0.22</td>
<td>0.36</td>
<td>80.6%/88.6%</td>
<td>87.2%</td>
<td>87.2%</td>
<td>0%</td>
</tr>
</tbody>
</table>

6.6. Discussions

In this section, based on the simulation results obtained, how each strategy may affect
performance parameters are discussed in detail. All the above strategies and performance parameters are included except for the proportion of the upper window open which is determined only by the environmental conditions. The percentages of increase/decrease in the questioned performance parameters caused by the application of each strategy are calculated. Five types of changes are categorised based on the significance in percentage difference: largely increase/decrease (≥20%), moderately increase/decrease (≥10% and <20%), slightly increase/decrease (≥1% and <10%), no change (<1%) and Vary. Vary denotes that a consistent relationship has not been found, as the relationship may be significantly affected by other strategies. Details about the relationships are illustrated in Table 6.6.1.

Except for the advanced window system, all other tested strategies play important roles in reducing average daily cooling energy consumptions. Overall, by adopting the MM system and the passive strategies of a light shelf and night cooling, the cooling energy consumption for the transitional season can be cut by about 90% (from 2.18 kWh/day to 0.22 kWh/day). By comparing S1 and S6, the MM system alone (excluding passive strategies and the benefits of a fan and other adaptive opportunities) contributes to about 22.4% of reduction (0.44 kwh/day out of 1.96 kWh/day). It proves the proposed MM system to be an effective way to reduce the reliance on AC systems. However, this study does not consider the energy costs of other components of the AC system, the MV system, the window automation system, the signalling system and the fan. Also, it has not analysed in detail the interactions between an AC system and MV system., Hence, it is necessary to conduct more thorough studies to select an appropriate HVAC system which can energy efficiently work well with other components of the MM system to guarantee the occupants’ comfort.

Fans and other adaptive opportunities (reflected through the increase in AC setpoint), a light shelf and night cooling are very effective in reducing the peak cooling load, whereas the optimal control of the lower window just slightly reduces the peak cooling load at the higher AC setpoint but largely reduces it at the lower AC setpoint. However, the changeover system and the advanced window system have ignorance effects on the peak cooling load. Overall,
the MM system and the associated passive strategies remarkably reduce the peak cooling load by over 80% (from 1.88 kW to 0.36 kW). By comparing S1 and S6, the MM system itself (excluding passive strategies and the benefits of a fan and other adaptive opportunities) contributes to about 5.2% of the reduction (0.08 kWh/day out of 1.52 kWh/day). The remarkable reduction in the peak cooling load indicates that a cooling system with a much smaller cooling capacity, smaller sized distribution ducts, supply and exhaust fans with lower power are required, leading to a considerable reduction in the initial cost of the HVAC system.

The use of the changeover system (together with the shift from ideal control to realistic AC system control) significantly reduces the percentage of time that the indoor air temperature meets the setpoint criteria. This percentage of time can be largely improved by using the advanced window system and can be moderately improved by applying the optimal control of the lower window. However, both strategies have less significant effects when the percentage of time is at higher levels. A light shelf can moderately increase the percentage of time (only tested at low levels), whereas night cooling can just slightly increase it (only tested at high levels). An inconsistent relationship between the increase in AC setpoint and the improvements in the percentage of time has been found, which can be explained by the fact that in each scenario the AC system is sized to just meet the corresponding peak load. Overall, even though the MM system and the passive strategies are applied, it still remains some points at which the indoor air temperature cannot meet the setpoint criteria. This is probably due to the fact that window operation alone is not capable of cooling down the room to a satisfied level. It may be also caused by the interchanges between the AC mode and NV mode when both the AC system and windows require some reaction time to enhance thermal conditions.

This may be resolved by using a more advanced AC system and more intelligent control logic. If a VAV AC system is used, a more precise control should be used to enable the supply volume flow rate to respond to both the cooling load of the controlled room and external environment. A VRF AC system may have a better performance as it uses refrigerant as the cooling means
instead of air and the former has a higher specific heat which may respond faster to the changes in cooling load. Some other advanced AC systems, such as radiant cooling system and displacement ventilation system, may also be considered. Moreover, the changeover between the HVAC systems and the window can be optimised. For example, due to the benefits of increasing air movements and letting in fresh air, the automatically controlled window may be switched on even when the internal temperature is higher than the external. The window type and operation principles should be more carefully designed in order to enhance the cooling capacity of window operations. Furthermore, the airflow network module of ESP-r treats the whole room as one temperature but, in practice, if the occupant sits near the window, he/she will benefit more from opening a window as discussed in Chapter 3.

The effects of the changeover system and night cooling on the lower window operations were not tested, and the optimal control of the lower window considerably changes the proportion of the lower window open but the magnitude of the proportion is merely determined by the setpoints behind the signalling system. Both the advanced window system and a light shelf slightly reduce the proportion of the lower window open, whereas the increase in AC setpoint resulted from using a fan and other adaptive opportunities significantly increase the proportion of the lower window open. All the influences of the three strategies result from the decrease/increase in indoor air/radiant temperature due to the intrinsic feature of the Rijal’s algorithm that more window opening actions occur at higher indoor operative temperatures. However, as discussed in Section 6.5, the action of using a fan and other adaptive opportunities itself considerably reduces the duration of the lower window open, which is consistent with the fact that when fans and other adaptive opportunities are available, occupants will rely less on windows to cool down the room.

Hence, the window operation behaviours can be to some extent manipulated by adaptive opportunities, the advanced window system and passive strategies. Therefore, these factors should be carefully dealt with or designed to promote energy efficient window operations. An
important point to note is that the optimal control of the lower window assumes that occupants follow the instructions of the signalling systems perfectly, but it is very difficult to achieve so in practice. Fast and correctly responds to the signalling system require the locations of the signal lights to be easily spotted (Ackerly and Brager, 2013). Additionally, the windows should be easily accessible, and occupants should be educated to understand the working principle behind the system.

Rijal et al. (2008) argue that it is the indoor temperature that determines window opening actions, while opening duration (or closing actions) is likely to be related to the outdoor temperature. However, the Rijal’s algorithm adopts the concept of “deadband” to simulate the closing actions instead of using a separate window closing probability correlated (e.g. the surviving model introduced by Haldi and Robinson (2009)) to the outdoor temperatures found in other stochastic window operation models like the ones developed by Haldi and Robinson (2009) and Yun and Steemers (2008). Also, the Rijal’s algorithm does not consider the facts that the probabilities of window operations at intermediate occupancy intervals differ from those at arrival and departure times. On the other hand, the Rijal’s algorithm is advantageous that it explicitly incorporates the effects of a fan and other possible adaptive behaviours and Rijal et al. (2011) further developed the algorithm by taking into consideration situation-specific motivations and constraints. Tahmasebi and Mahdavi (2016) argue that all the Rijal’s algorithm and the stochastic models developed by Haldi and Robinson (2009) and Yun and Steemers (2008) can accurately predict window operation actions provided that their key parameters are modulated to meet the features of the building under study. Hence, the Rijal’s algorithm should be further developed by adopting the merits of the stochastic models developed by Haldi and Robinson (2009) and when it is applied, it is necessary to modify some of its parameters by considering the features of the building under study and the local climate.

An important point to note is that the proportion of the lower window open obtained in S2 when other adaptive behaviours are available is 56.1%, which compares well with the value of about 50% found in the field study at 26°C as shown in Figure 5.4.7 in Chapter 5.
It has been found that the advanced window system is capable of reducing the reliance on AC systems, and it also leads to averagely lower indoor temperatures which in turn slightly reduces the proportion of time that the lower window is open and misuses of the lower window. However, it is not clear that how the automatically controlled upper window itself may affect occupant’ perceptions of and their habits of interactions with the environment. In particular, there is no deadband of window automation included in current simulations so that windows are frequently opened/closed which may cause distractions for occupants. Hence, a deadband should be considered for window automation and it needs further studies on the influences of the upper window in practice.

Another issue concerning window operation controls is that current simulations employ a sudden change in window position which may lead to high fluctuations in the indoor thermal environment. This can be overcome by using a precise position control to determine the opening area of the windows based on feedbacks of wind velocity, the external and internal temperatures, etc. A fuzzy controller introduced by Marjanovic and Eftekhari (2004) and model predictive control (MPC) strategies (Spindler and Norford, 2009a; Spindler and Norford, 2009b; Hu and Karava, 2014) are two possible ways to realise the precise position control. The MPC may also be used to optimise the energy performances of the components of an HVAC system, the integrated shading devices and night cooling in an MM building (Spindler and Norford, 2009a; Spindler and Norford, 2009b; Hu and Karava, 2014).

The adaptive behaviours, including window and fan operations as well as other adaptive opportunities, are found to be energy efficient ways to maintain comfort, so it is necessary to promote their applications in offices. To make full use of the adaptive behaviours, they ought to be easily accessible (excluding the thermostats) and their effectiveness is well understood by occupants. Moreover, since an MV system is not included in the simulations, studies should be conducted on how an MV system works with the other systems. In particular, more detailed control algorithms should be derived to deal with the conflicts between cooling and fresh air requirements.
Other limitations of this study include that it just focuses on a transitional season and the performance of a one-person single office. Further studies should be conducted on the year-round performances of more complicated spaces. Additionally, the effect of humidity is neglected in this study and further studies should be conducted to deal with it, but previous studies show that residents in a humid climate are likely to adapt to the humid environment and not sensitive to the changes in humidity conditions (Givoni et al., 2004; Nejad and van Meeteren, 2008; Wu, 2015).
Table 6.6.1. Summary of the relationships between strategies and performance parameters.

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Average daily cooling energy consumption</th>
<th>Peak cooling load</th>
<th>% room air temperature meeting the setpoint criteria</th>
<th>% Lower window open</th>
<th>% window misuse time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changeover system (realistic AC system control)</td>
<td>Largely decrease</td>
<td>No change*</td>
<td>Largely decrease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A fan and other adaptive opportunities (increase in AC setpoint)</td>
<td>Largely decrease</td>
<td>Largely decrease</td>
<td>Vary</td>
<td>Largely increase</td>
<td>Largely decrease</td>
</tr>
<tr>
<td>Advanced window system</td>
<td>Slightly decrease</td>
<td>No change</td>
<td>Largely increase (less significant for low levels)</td>
<td>slightly decrease</td>
<td>No change/ slightly decrease</td>
</tr>
<tr>
<td>Optimal control of the lower window</td>
<td>Largely decrease</td>
<td>Slightly decrease (depending on the AC setpoint)</td>
<td>Moderately increase (less significant for high levels)</td>
<td>Vary</td>
<td>Largely decrease</td>
</tr>
<tr>
<td>Light shelf</td>
<td>Largely decrease</td>
<td>Largely decrease</td>
<td>moderately increase (only tested at low levels)</td>
<td>Slightly decrease</td>
<td>No change</td>
</tr>
<tr>
<td>Night cooling</td>
<td>Largely decrease</td>
<td>Largely decrease</td>
<td>slightly increase (only tested at high levels)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* as discussed above, the AC system with changeover is sized according to the peak cooling load of the system without changeover.

6.7 Summary

Based on the previous adaptive thermal comfort studies and the analysis of existing MM buildings, this chapter proposes an MM system which encourages occupants to exercise adaptive opportunities and improves both comfort levels and energy efficiency. The MM system integrates an advanced window system, a signalling system and an associated HVAC
system. By applying this MM system and the associated passive energy-saving strategies (i.e. the light shelf and night ventilation), an overall reduction in cooling energy of about 90% during transitional seasons compared to a conventional air-conditioned building is achieved. The MM system and the associated passive energy-saving strategies also remarkably cut the peak cooling load by over 80% leading to a significant decrease in initial investment in the associated HVAC system. However, according to the results of building performance simulations, even though the MM system and the passive strategies are applied, it still remains some points at which the indoor air temperature cannot meet the setpoint criteria. This is probably due to the fact that window operation alone is not capable of cooling down the room to a satisfied level. It may be also caused by the interchanges between the AC mode and NV mode when both the AC system and windows require some reaction time to enhance thermal conditions. This chapter has also explored how the alternative method of predicting adaptive thermal comfort and stochastic behaviour models may be used in behaviour modelling to more accurately predict energy performances and comfort levels of real buildings.
7. Conclusions and Future Work

7.1 Conclusion

This study has shown a strong relationship between adaptations and thermal comfort levels. Among the three categories of adaptations, namely physiological, psychological and behavioural adaptations, behavioural adaptations have been verified to play significant roles and can be relatively easily quantified, and therefore is the focus of this study. The capabilities of ten adaptive behaviours in increasing occupants’ thermal comfort temperatures are quantified and their interactions are evaluated through theoretical studies. Some effective adaptive behaviours are studied in detail through lab experiments and field studies, and proved to be very beneficial to thermal comfort. It also demonstrates an application of the adaptive theories in mixed mode buildings to determine changeover temperatures and shows a significant energy conservation potential. This study has achieved the research objectives as demonstrated below:

According to Chapter 2, physiological and psychological adaptations are abstract, and it is very difficult to quantify their effectiveness. Behavioural adaptations, on the other hand, are virtual and their effectiveness are widely recognised, and therefore are the main components of the thermal comfort temperature model. Adaptive increments of ten adaptive behaviours are investigated by using the SET* model and CFD simulations on the basis of previous literature. The factors affecting the adaptive increment of adaptive behaviours are identified, namely interactions among adaptive behaviours, constraints of adaptive behaviours, psychological and physiological effects. The factors can be accounted for by using a correction factor introduced in Chapter 3.

Chapter 4 demonstrates a lab experiment that adopts a climate chamber with human subjects to verify and develop the results of the theoretical study in Chapter 3. This chapter has found the adaptive increment of taking cold water to be 1.5°C which is much more significant than previous literature suggests, and the overall adaptive increment is as high as 4.7°C when all the studied adaptive behaviours are exercised. According to the field study results in Chapter 5, the thermal
comfort temperature of occupants increases by at least 1°C when desk fans and cool mats are available.

Chapter 5 contains an online survey which evaluates the availability of adaptive opportunities and how occupants perceive these adaptive opportunities in practice. Results show that office users in East China rely largely on AC systems for cooling and use windows more frequently to get fresh air or air movement rather than cooling down the room. Only 6.11% of survey respondents are not able to operate windows, indicating most offices in the area are equipped with openable windows. However, there is a low availability of other adaptive opportunities, including those experimentally proved to be effective in improving thermal comfort in Chapter 4: only about 50%, 20% and 14.5% of office users have access to fans, cool mats (or non-upholstered chairs) and cold water. Although some adaptive opportunities are very effective in improving thermal comfort, office users are unfamiliar with their effectiveness and may tend to use those familiar adaptive opportunities. For example, Chapter 4 has proved that drinking cold water is a very effective way of cooling, but it only ranks seventh among the most effective ways of cooling in this survey.

In Chapter 5, statistically strongly stochastic models of using AC, windows, desk fans and cool mats have been developed. It is worth noting that the stochastic model of cool mat usage is one of the first attempts to study cool mat usage in detail. These stochastic models assist to identify some issues associated with exercising adaptive opportunities in practice (e.g. low operation frequency of desk fans and misuses of windows and AC) and evaluate how the availability of other adaptive behaviours affects the use of AC and windows. According to Chen et al. (2014), the involvement of energy concerns will largely reduce AC usage without compromising thermal comfort, so it should be considered in the MM building designs to achieve better energy performances.

The lab experiment also shows that over 80% of the participants can still find it thermally acceptable at an operative temperature of 30°C on the condition that adequate adaptive opportunities are provided. The field studies have shown that occupants can accept an operative temperature of 28°C and this temperature may increase when more adaptive opportunities are
available. The comfort temperature is highly related to available adaptive opportunities and can be used as the changeover temperature for a mixed mode system.

Chapter 6 proposes an MM system which encourages occupants to exercise adaptive opportunities and improves both comfort levels and energy efficiency. The MM system integrates an advanced window system, a signalling system and an associated HVAC system. By applying this MM system and the associated passive energy-saving strategies (i.e. the light shelf and night ventilation), an overall reduction in cooling energy of about 90% during transitional seasons compared to a conventional air-conditioned building is achieved. The MM system and the associated passive energy-saving strategies also remarkably cut the peak cooling load by over 80%, leading to a significant decrease in initial investment in the associated HVAC system. This chapter has also explored how the adaptive thermal comfort theories and stochastic behaviour model may be used in behaviour modelling to more accurately predict energy performances and comfort levels of real buildings.

7.2 New contributions to the field
Among the three categories of adaptations, namely physiological, psychological and behavioural adaptations, behavioural adaptations have been demonstrated to be relatively easily quantified. This thesis has studied the quantification of adaptive behaviours in detail: verifying or improving the previous quantification results (adaptive increments) through theoretical studies, lab experiments and field studies. For example, the adaptive increment of taking cold water was found to be 1.5°C which is much more significant than the previous literature suggests. This thesis introduces an empirical correction factor to the overall adaptive increment. The correction factor enables to include the effects of psychological adaptations, physiological adaptations, interactions among behavioural adaptations and control constraints when quantifying adaptive behaviours. According to lab experiment results, most participants find an operative temperature of 30°C acceptable when they are provided with abundant adaptive opportunities. Based on the results from field studies, stochastic behaviour models were derived for the local climate and the stochastic model of using cool mat was derived for
the first time. This thesis has also demonstrated how the adaptive thermal comfort theories may be applied to a mixed mode system (e.g. using adaptive increments and the empirical correction factor to determine the changeover temperature of a mixed mode system) and demonstrates a significant energy conservation potential.

7.3 Future work

To further validate the obtained results, it is necessary to enlarge the example size of the lab experiment, survey and field studies. Also, the adaptive opportunities that have not been analysed in lab experiments or field studies need further justifications. Since this study mainly focuses on behavioural adaptations, psychological and physiological adaptations should be studied in more detail in future studies. Moreover, it needs more efforts to validate the alternative method of predicting adaptive thermal comfort and develop the method for wider applications (e.g. extending its application to evaluate adaptations in a cold environment).

Some issues associated with the studied adaptive opportunities have been revealed, such as the existence of constraints of using adaptive behaviours, low availability of some effective adaptive opportunities, the low operation frequency of desk fans and misuses of windows and AC systems. Hence, it is necessary to provide office users with abundant effective and easy-to-use adaptive opportunities. Moreover, it is essential to educate occupants about the effectiveness of adaptive opportunities and guide them to more frequently and correctly exercise the adaptive opportunities. The obtained stochastic models of AC usage, window operation, using desk fans and cooling mats should be improved by including other factors affecting the use of the adaptive behaviours. The factors may comprise air quality, time of a day, active/passive user factor, ease of use factor, socio-cultural factors, the availability of other adaptive opportunities, etc. For example, as air quality has been found to be an important factor affecting window operation, both indoor temperature and air quality may be regarded as variables to form a multi logit regression to represent the probability of window operation. Socio-cultural factors, such as office hierarchy, working hours and energy conservation consciousness, may also significantly affect these adaptive behaviours. Other
examples include operating a blind is highly related to solar radiation and have old drink may be largely affected by thirsty sensations

The proposed MM system may not guarantee that the indoor thermal environment can always meet the setpoint criteria. This may be resolved by using a more advanced AC system and a more intelligent control logic. If a VAV AC system is used, a more precise control should be used to enable the supply volume flow rate to respond to both the cooling load of the controlled room and external environment. A VRF AC system may have a better performance as it uses refrigerant as the cooling means instead of air and the former has a higher specific heat which may respond faster to the changes in cooling load. Some other advanced AC systems, such as radiant cooling system and displacement ventilation system, may also be considered. Moreover, the changeover between the HVAC systems and the window should be optimised. For example, due to the benefits of increasing air movements and letting in fresh air, the automatically controlled window may be switched on even when the internal temperature is higher than the external. The window type and operation principles should be more carefully designed to enhance the cooling capacity of window operations.

Other limitations of this study include that it just focuses on summer and transitional seasons. Further studies should be conducted on year-round performances. Among the ten adaptive behaviours studied in this research, some of them, such as activity adjustment and posture adjustment, are not evaluated in detail, so further targeting studies are required. Since this study as conducted in Chinese context, it is necessary to extend the results obtained from this study to western and other context by further conducting researches in the context. The effect of humidity is neglected in this study, although previous studies show that residents in a humid climate are likely to adapt to the humid environment and not sensitive to the changes in humidity conditions (Givoni et al., 2004; Nejad and van Meeteren, 2008; Wu, 2015).
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Appendix

Appendix 4.1. Questionnaire for the dynamic study of the lab experiment

Gender: □ Male □ Female
Height_____ cm       Weight_____kg       Age_____   

Initial Stage
1. Your current thermal sensation is:

2. Is your current thermal environment acceptable?
   (1) If yes, the degree of acceptance is:  
      +0  +1
      Just acceptable  Clearly acceptable
   (2) If no, the degree of unacceptance is:  
      -0  -1
      Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?
   (1) If yes, the degree of acceptance is:  
      +0  +1
      Just acceptable  Clearly acceptable
   (2) If no, the degree of unacceptance is:  
      -0  -1
      Just acceptable  Clearly acceptable
The First Stage

1. Your current thermal sensation is:

   -3  -2  -1  0  1  2  3
   Cold  Cool  Slightly cool  Neutral  Slightly warm  Warm  Hot

2. Is your current thermal environment acceptable?

   (1) If yes, the degree of acceptance is: +0  +1
       Just acceptable  Clearly acceptable

   (2) If no, the degree of unacceptance is: -0  -1
       Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?

   (1) If yes, the degree of acceptance is: +0  +1
       Just acceptable  Clearly acceptable

   (2) If no, the degree of unacceptance is: -0  -1
       Just acceptable  Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.
   □ Yes  □ No  You want the air speed to be: □ higher  □ remain unchanged  □ lower

The Second Stage

1. Your current thermal sensation is:

   -3  -2  -1  0  1  2  3
   Cold  Cool  Slightly cool  Neutral  Slightly warm  Warm  Hot

2. Is your current thermal environment acceptable?

   (1) If yes, the degree of acceptance is: +0  +1
       Just acceptable  Clearly acceptable

   (2) If no, the degree of unacceptance is: -0  -1
       Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?
4. Have you used the desk fan during this stage? If so, please comment on the air speed.
☐ Yes  ☐ No   You want the air speed to be: ☐ higher ☐ remain unchanged ☐ lower

The Third Stage
1. Your current thermal sensation is:

   3  2  1  0  1  2  3
   Cold  Cool  Slightly cool  Neutral  Slightly warm  Warm  Hot

2. Is your current thermal environment acceptable?

   3  2  1  0  1  2  3
   Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?

   3  2  1  0  1  2  3
   Just acceptable  Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.
☐ Yes  ☐ No   You want the air speed to be: ☐ higher ☐ remain unchanged ☐ lower

The fourth Stage
1. Your current thermal sensation is:

   3  2  1  0  1  2  3
   Cold  Cool  Slightly cool  Neutral  Slightly warm  Warm  Hot

2. Is your current thermal environment acceptable?
3. Is your current air quality level acceptable?

(1) If yes, the degree of acceptance is: +0
                                            +1
                                              
                                              Just acceptable   Clearly acceptable
(2) If no, the degree of unacceptance is: -0
                                            -1
                                              
                                              Just acceptable   Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.

☐ Yes  ☐ No  You want the air speed to be: ☐ higher  ☐ remain unchanged  ☐ lower
Appendix 4.2. Questionnaire for the static temperature study of the lab experiment

Gender: □ Male       □ Female
Height_____ cm       Weight______kg       Age_____

Initial Stage

1. Your current thermal sensation is:

2. Is your current thermal environment acceptable?
   (1) If yes, the degree of acceptance is: +0                 +1
       Just acceptable   Clearly acceptable
   (2) If no, the degree of unacceptance is: -0                 -1
       Just acceptable   Clearly acceptable

3. Is your current air quality level acceptable?
   (1) If yes, the degree of acceptance is: +0                 +1
       Just acceptable   Clearly acceptable
   (2) If no, the degree of unacceptance is: -0                 -1
       Just acceptable   Clearly acceptable

The First Stage
1. Your current thermal sensation is:

<table>
<thead>
<tr>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
</tbody>
</table>

2. Is your current thermal environment acceptable?

(1) If yes, the degree of acceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?

(1) If yes, the degree of acceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.
   ☐ Yes   ☐ No  You want the air speed to be:  ☐ higher  ☐ remain unchanged  ☐ lower

The Second Stage

1. Your current thermal sensation is:

<table>
<thead>
<tr>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
</tbody>
</table>

2. Is your current thermal environment acceptable?

(1) If yes, the degree of acceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?

(1) If yes, the degree of acceptance is:  
-0  0  1
Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is:  
-0  0  1
Just acceptable  Clearly acceptable
4. Have you used the desk fan during this stage? If so, please comment on the air speed.
☐ Yes  ☐ No  You want the air speed to be: ☐ higher  ☐ remain unchanged  ☐ lower

The Third Stage
1. Your current thermal sensation is:

<table>
<thead>
<tr>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
</tbody>
</table>

2. Is your current thermal environment acceptable?

(1) If yes, the degree of acceptance is: ☐ +0  ☐ +1

Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is: ☐ -0  ☐ -1

Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?

(1) If yes, the degree of acceptance is: ☐ +0  ☐ +1

Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is: ☐ -0  ☐ -1

Just acceptable  Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.
☐ Yes  ☐ No  You want the air speed to be: ☐ higher  ☐ remain unchanged  ☐ lower

The fourth Stage
1. Your current thermal sensation is:

<table>
<thead>
<tr>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
</tbody>
</table>

2. Is your current thermal environment acceptable?

(1) If yes, the degree of acceptance is: ☐ +0  ☐ +1

Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is: ☐ -0  ☐ -1

Just acceptable  Clearly acceptable

3. Is your current air quality level acceptable?
4. Have you used the desk fan during this stage? If so, please comment on the air speed.
☐ Yes ☐ No You want the air speed to be: ☐ higher ☐ remain unchanged ☐ lower

The Fifth Stage

1. Your current thermal sensation is:

<table>
<thead>
<tr>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
</tbody>
</table>

2. Is your current thermal environment acceptable?

(1) If yes, the degree of acceptance is: [ ] +0 +1
Just acceptable Clearly acceptable

(2) If no, the degree of unacceptance is: [ ] -0 -1
Just acceptable Clearly acceptable

3. Is your current air quality level acceptable?

(1) If yes, the degree of acceptance is: [ ] +0 +1
Just acceptable Clearly acceptable

(2) If no, the degree of unacceptance is: [ ] -0 -1
Just acceptable Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.
☐ Yes ☐ No You want the air speed to be: ☐ higher ☐ remain unchanged ☐ lower

The Sixth Stage

1. Your current thermal sensation is:

<table>
<thead>
<tr>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Cool</td>
<td>Slightly cool</td>
<td>Neutral</td>
<td>Slightly warm</td>
<td>Warm</td>
<td>Hot</td>
</tr>
</tbody>
</table>

2. Is your current thermal environment acceptable?
3. Is your current air quality level acceptable?

(1) If yes, the degree of acceptance is:  \[ +0 \quad +1 \]

Just acceptable  Clearly acceptable

(2) If no, the degree of unacceptance is:  \[ -0 \quad -1 \]

Just acceptable  Clearly acceptable

4. Have you used the desk fan during this stage? If so, please comment on the air speed.

☐ Yes  ☐ No  You want the air speed to be:  ☐ higher  ☐ remain unchanged  ☐ lower
Appendix 5.1. A survey on office adaptive behaviours in Eastern China

1. Which city does your office locate

________________

2. What is the type of your office
   ○ One-person private office
   ○ Two-person private office
   ○ Multi-person private office
   ○ Open plan office

3. Are you able to manually open your office window(s) easily at your seat?
   ○ Easy
   ○ Relatively easy
   ○ Relatively difficult
   ○ Difficult
   ○ Window cannot be manually opened

4. Does your office install an air conditioning system?
   ○ Yes, central air conditioning (AC) system
   ○ Yes, split AC system
   ○ No

5. Does your office install a mechanical system?
   ○ Yes
   ○ No
   ○ Have no idea

6. Do you use fans in your office?
○ Yes, ceiling fan
○ Yes, desk fan
○ Yes, floor standing pedestal fan
○ No

7. Is ice water provided in your office?
   ○ Yes
   ○ No

8. Does your office have strict dress code?
   ○ Yes
   ○ No

9. What is type of your office chair?
   ○ Soft (cloth/leather finish) Chair, no cool mat
   ○ Soft (cloth/leather finish) Chair, with cool mat
   ○ Hard (Wood/plastic finish) Chair, no cool mat
   ○ Hard (Wood/plastic finish) Chair, with cool mat
   ○ Others, please specify ______________

10. During summer (when AC systems are often used), what is your purpose of opening a window? (Please rank the following purposed, 1 refers to the most important purpose and 6 refers to the least important one; it is not essential to rank all the options)
   □ Bringing in fresh air
   □ Bringing in cool air to cool down the room
   □ Circulating air to increase air movement
   □ Getting rid of dust and bacteria
   □ Allowing sunlight in
   □ Connecting to the outdoors
11. Will you keep the window(s) open when you are using air conditioning systems?
   ○ Often
   ○ Accidentally
   ○ Never

12. During transitional seasons ((when AC systems are not often used), what is your purpose of opening a window? (Please rank the following purposes, 1 refers to the most important purpose and 6 refers to the least important one; it is not necessary to rank all the options)
   □ Bringing in fresh air
   □ Bringing in cool air to cool down the room
   □ Circulating air to increase air movement
   □ Getting rid of dust and bacteria
   □ Allowing sunlight in
   □ Connecting to the outdoors

13. What do you think is the most effective way(s) of improving thermal comfort in office? (Please rank the following positions, 1 refers to the most important and 12 refers to the least important; it is not essential to rank them all)
   □ Air conditioning system
   □ Fan
   □ Opening window
   □ Wearing thin clothes
   □ Drinking cold water
   □ Using cool mat
   □ Operating curtain to prevent sunshine
   □ Using wet wipe
   □ Having a siesta
   □ Stretching your body
☐ Slowing down body movement
☐ Moving to cooler space
Appendix 5.2 A survey on the activeness of field study participants on exercising adaptive behaviours

1. If you can easily access to the air conditioning system in your office, how often would you use it when you feel warm?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

2. If you can easily access to windows in your office, how often would you use them when you feel warm?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

3. If you can easily control blinds in your office, how often would you use them?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

4. How often would you have a siesta?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never
5. If you have an easily accessible fan in your office, how often would you use it when you feel warm?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

6. If you have a cool mat available in your office, how often would you use it when you feel warm?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

7. If you are provided with cold water in your office, how often would you drink it when you feel warm?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

8. If you have prepared thinner clothes in your office, how often would you change clothes when you feel warm?
   ○ Often
   ○ Sometimes
   ○ Rarely
   ○ Never

9. If you have prepared wet wipes in your office, how often would you use them when you
feel warm?
○ Often
○ Sometimes
○ Rarely
○ Never

10. What do you think is the most important factor(s) that affect your overall comfort level/working productivity? (Please rank the following factors; 1 refers to the most important one while 8 refers to the least important one; it is not essential to rank them all)
□ Too warm or too cool
□ Too much air movement
□ Bad indoor air quality
□ Too dry or too humid
□ Glare or too much light, shadows or too little light or
□ Too noisy
□ Bad office layout
□ Distractions from other occupants in the room
Appendix 5.3. A survey on the activeness of exercising adaptive behaviours (no additional adaptive behaviours)

1. Name: __________ clothing insulation (calculation method): __________

2. Did you just arrive in this room (have been in this room for less than 30 min) ?
   ○ No ○ Yes

3. Are you using AC system now?
   ○ No ○ Yes (AC system setpoint is __________)

4. What’s your current thermal sensation?
   ○ Cold ○ Cool ○ Slightly cool ○ Neutral ○ Slightly warm ○ Warm ○ Hot

5. What’s your current thermal comfort level?
   ○ Comfortable ○ Slightly uncomfortable ○ Uncomfortable ○ Very uncomfortable

6. You want the room temperature to be
   ○ Cooler ○ No change ○ Warmer
Appendix 5.4. A survey on the activeness of exercising adaptive behaviours (additional adaptive behaviours are available)

1. Name: __________ clothing insulation (calculation method): __________

2. Did you just arrive in this room (have been in this room for less than 30 min)?
   ○ No ○ Yes

3. Are you using AC system now?
   ○ No ○ Yes (AC system setpoint is ________)

4. Are you using the desk fan now?
   ○ Yes ○ No

5. Are you using a cool mat now?
   Yes No

6. What’s your current thermal sensation?
   ○ Cold ○ Cool ○ Slightly cool ○ Neutral ○ Slightly warm ○ Warm ○ Hot

7. What’s your current thermal comfort level?
   ○ Comfortable ○ Slightly uncomfortable ○ Uncomfortable ○ Very uncomfortable

8. You want the room temperature to be
   ○ Cooler ○ No change ○ Warmer
Table 7. Steps in the Implementation of the Adaptive Algorithm in ESP-r (continued)

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Indoor air temp.</td>
<td>$T_{ia}$</td>
<td>1/h</td>
<td>Available at each timestep (variable)</td>
</tr>
<tr>
<td>12</td>
<td>Indoor operative temp.</td>
<td>$T_{op}$</td>
<td>1/h</td>
<td>Available at each timestep (50% min, 50% $T_{ia}$)</td>
</tr>
<tr>
<td>13</td>
<td>Outdoor air temp.</td>
<td>$T_{oa}$</td>
<td>1/h</td>
<td>Interpolated from climate file (hourly data in file)</td>
</tr>
<tr>
<td>14</td>
<td>Daily mean outdoor air temp.</td>
<td>$T_{oa\text{mean}}$</td>
<td>1/day</td>
<td>Calculated from 24 hourly data points per day</td>
</tr>
<tr>
<td>15</td>
<td>Running mean outdoor air temp.</td>
<td>$T_{ra}$</td>
<td>1/day</td>
<td>Initial value calculated from previous 20 days daily mean then $T_{ra}=1-(1-\alpha)T_{oa\text{mean}}+\alpha T_{oa\text{mean}-2}+\alpha^2T_{oa\text{mean}-3}$</td>
</tr>
</tbody>
</table>

**Selection of mode**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Determine mode</td>
<td>Mode</td>
<td>1/day</td>
<td>if ACavail = Yes and $T_{oa}&gt;28.1^\circ C$ then Mode = AC if Hail = Yes and $T_{oa} \leq 10^\circ C$ then Mode = Heating else Mode = Free running</td>
</tr>
</tbody>
</table>

**Status of window, fan and door**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Status of window (0 = closed)</td>
<td>$Sw$</td>
<td>1/h</td>
<td>Initial values set to 0. Then set by previous timestep.</td>
</tr>
<tr>
<td>18</td>
<td>Status of fan (0 = off)</td>
<td>$Sf$</td>
<td>1/h</td>
<td>Initial values set to 0. Then set by previous timestep.</td>
</tr>
<tr>
<td>19</td>
<td>Status of door (0 = closed)</td>
<td>$Sd$</td>
<td>1/h</td>
<td>Initial values set to 0. Then set by previous timestep.</td>
</tr>
</tbody>
</table>

**Determine comfort temp. from mode and previous fan status**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Determine comfort temperature</td>
<td>$T_{conf}$</td>
<td>1/day</td>
<td>if Mode = AC, $T_{conf} = 0.416(T_{oa}+16.5)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>if Mode = Heating, $T_{conf} = 0.556(T_{oa}+19.1)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>if Mode = Free running (includes NC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>if $Sf = 0$, $T_{conf} = 0.408(T_{oa}+16.6)$ (without fan effect)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>if $Sf = 1$, $T_{conf} = 0.408(T_{oa}+16.6)$ (with fan effect)</td>
</tr>
</tbody>
</table>

**Window status (Free running or Heating)**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Free running or heating?</td>
<td>Mode</td>
<td>1/day</td>
<td>if Mode = Heating or Free running</td>
</tr>
<tr>
<td>22</td>
<td>Logit function for window</td>
<td>$FuncW = \logit(Pw) = 0.525(T_{ao}-T_{conf})/0.5$</td>
<td>1/h</td>
<td>if $Sw = 0$, $Pw = \exp(\text{FuncW})/(1+\exp(\text{FuncW}))$, else $Pw = 0$</td>
</tr>
<tr>
<td>23</td>
<td>Probability for window open</td>
<td>$Pw$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>24</td>
<td>Random number between 0 and 1</td>
<td>$Rw$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>25</td>
<td>Window opening effectiveness</td>
<td>$Weff$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>26</td>
<td>Window status (0 = closed, 1 = open)</td>
<td>$Sw$</td>
<td>1/h</td>
<td>if $Pw &gt; Rw$ then window open ($Sw = 1$)</td>
</tr>
<tr>
<td>27</td>
<td>If 5°C hotter outside: close window?</td>
<td>$Sw$</td>
<td>1/h</td>
<td>if $Rw \geq Pw$ then window closed ($Sw = 0$)</td>
</tr>
<tr>
<td>28</td>
<td>Night cooling mode, open if $T_{ra} &lt; 1$</td>
<td>$NC$</td>
<td>1/h</td>
<td>if $NC\text{pass} = \text{Yes}$ and $T_{ra} &lt; 28.1^\circ C$ then $Sw = 1$</td>
</tr>
</tbody>
</table>

**Window status (AC)**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>AC?</td>
<td>Mode</td>
<td>1/day</td>
<td>if Mode = AC, $Sw = 0$ (windows closed if AC mode)</td>
</tr>
</tbody>
</table>

**Fan status (free running)**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Free running?</td>
<td>Mode</td>
<td>1/day</td>
<td>if Mode = Free running</td>
</tr>
<tr>
<td>31</td>
<td>Logit function for fan</td>
<td>$FuncF = \logit(Pf) = 0.995(T_{ao}-T_{conf})/(0.5)^2FD$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>32</td>
<td>Probability for fan on</td>
<td>$Pf$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>33</td>
<td>Random number between 0 and 1</td>
<td>$Rf$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>34</td>
<td>Fan status (0 = off, 1 = on)</td>
<td>$Sf$</td>
<td>1/h</td>
<td>if $Pf &gt; Rf$ then fan on ($Sf = 1$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>if $Rf \geq Pf$ then fan off ($Sf = 0$)</td>
</tr>
</tbody>
</table>

**Fan status (Heating or AC)**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>AC?</td>
<td>Mode</td>
<td>1/day</td>
<td>if Mode = AC, $Sf = 1$ (fans on if AC mode)</td>
</tr>
<tr>
<td>36</td>
<td>Heating?</td>
<td>Mode</td>
<td>1/day</td>
<td>if Mode = Heating, $Sf = 0$ (fans off if heating mode)</td>
</tr>
</tbody>
</table>

**Fan heat gains**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>Additional heat gains for fan</td>
<td>$Gfan$</td>
<td>1/h</td>
<td>Generated from thermal calculations</td>
</tr>
</tbody>
</table>

**Door status (all modes)**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Formula/Condition</th>
<th>Mode</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>Logit function for door</td>
<td>$FuncD = \logit(Pd) = 0.081(T_{ao}-1)$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>39</td>
<td>Probability for door open</td>
<td>$Pd$</td>
<td>1/h</td>
<td>if $Dpass = \text{Yes}$, $Pd = \exp(\text{FuncD})/(1+\exp(\text{FuncD}))$, else $Pd = 0$</td>
</tr>
<tr>
<td>40</td>
<td>Random number between 0 and 1</td>
<td>$Rd$</td>
<td>1/h</td>
<td>Generated from Fortran RNG.</td>
</tr>
<tr>
<td>41</td>
<td>Door status (0 = closed, 1 = open)</td>
<td>$Sd$</td>
<td>1/h</td>
<td>if $Pd &gt; Rd$ then door open ($Sd = 1$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>if $Rd \geq Pd$ then door closed ($Sd = 0$)</td>
</tr>
</tbody>
</table>