Assessing the effect of new control and payment methods on heating energy consumption and occupant behaviour in Chinese dwellings

by

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Doctoral Thesis

Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University

(November 2016)

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

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ABSTRACT

Energy demand reduction has become a global issue involving all countries, including China. As major energy consumers in today's society, the need for buildings to be built and operated more energy efficiently is well recognized. In 1995, the national standard on building energy efficiency in China (JGJ 26-95) was refined and updated to become the new residential Buildings standard (JGJ 26-2010) published in 2010. In the new version, many changes have been made to support the construction of more energy efficient buildings in China. For example, in the new standard, all buildings are highly recommended to install personal control on the heating system, such as by Thermostatic Radiator Valves (TRVs), together with 'pay for what you use' tariffs. Previous practice comprised uncontrolled heating with payment based on floor area. In order to reduce building energy consumption, Chinese government has revised the Chinese building design standard. In the new guide the use of individual room temperature control is highly recommended for new and refurbishment buildings. However, evidence to quantify the extent to which this improvement impact upon on the building energy consumption is currently lacking.

This thesis evaluates the impact of updated building design standards on thermal conditions and energy consumption in Chinese residential buildings. In order to evaluate the impact on the building energy consumption, two types of residential buildings have been chosen, one complying with the old Chinese building design standard, while the other complies with the new standard. The study was carried out in seven apartments in each type of building, a total of fourteen apartments and comprised with a longitudinal monitoring of indoor air temperature, outdoor air temperature, window position and energy consumption of each apartment. The impact of the new design standard has been evaluated in relation to a number of aspects, that include building construction, indoor thermal environment, occupant behaviour, thermal comfort and building energy consumption. It is concluded that updating the building design standard has had a positive influence on the building conditions and energy consumption. Furthermore, a thermal comfort survey was carried out in both new and old apartments according to updated standards. The

results show that the Predicted Mean Vote (PMV) model has a efficiently adequate predictor of occupants’ thermal comfort in both type of apartments. Thereby allowing confirmation that the new control refine did not compromise on thermal comfort. The percentage of acceptable of occupants is higher in new apartments compared with the old apartments.

ACKNOWLEGEMENTS

Firstly, I am deeply indebted to my two supervisors: Dr Mahroo Eftekhari and Professor Dennis Loveday. I would like to thank them for their great support and advice during my PhD studies as well as in the writing of this thesis. They provide their critical insight, experience, patience and encouragement to keep me working on my project and thesis. I would also like to thank the staff and other PhD students in the School of Civil and Building Engineering as they provided continuous help and advice. Finally, I also appreciate all help and support from my parents, family members and friends in China.

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Symbols	Description	Units
a	constants	[−]
A	Area of surface of building	[m^2]
A_{floor}	Floor areas of each apartment	[−]
b	The regression coefficient for Indoor or outdoor temperature	[−]
b	constants	[−]
c	The constant in the regression equation	[−]
Cp	Specific heat of water	[4.2J/kg °C]
d	The thickness of the material	[mm]
D	Diameter of the globe	[mm]
Ed	The heat loss by water vapour diffusion through the skin	[−]
E_{sw}	The heat loss by evaporation of sweat from the surface of the skin	[−]
E_{res}	The latent respiration heat loss	[−]
f_b	Basic energy price	[−]
f_h	Heating price per meter square per month	[−]
f_m	Actual metered energy use	[kWh]
f_Q	Heating price per kWh	[−]
H	The internal heat production	[−]
h_r	Heat transfer coefficient by radiation	[W/ (m^2•K)]
h_c	Heat transfer coefficient by convection	[W/ (m^2•K)]

K	The heat transfer from the skin to the outer surface of the clothed body	[−]
L	The dry respiration heat loss	[−]
m	Mass flow rate of water in pipes	[Kilograms]
N	Number of fresh air change per hour of the building	[ac/h]
p	The probability that the window is open	[−]
Q	The quantity of the heat	[W]
Q_v	Ventilation heat loss	[Watts]
Q_t	Total heating energy use metered by heat meter devices	[KWh]
Q_f	Fabric heat loss	[Watts]
R	The heat transfer by radiation from clothing surface	[−]
R_{si}	The resistivity of a "boundary layer" of air on the inside surface	[−]
R_{se}	The resistivity of the "air boundary layer" on the outside surface of the wall	[−]
Tin-p	Temperature from input pipe	[°C]
Tout-p	Temperature of output pipe	[°C]
T_{in}	Internal temperature of building	[°C]
T_{out}	external temperature of building	[°C]
T	the outdoor or indoor temperature	[−]
t_a	Air temperature	[°C]
t_g	Globe temperature	[°C]
t_o	Operative temperature	[°C]
t_r	Mean radiant temperature	[°C]
U	Thermal transmittance (U-value) of building elements	[W/m^2 °C]

V	Volume of the inside space of the building	[−]
V	The volume of the liquid passed through the flow sensor	[kg/s]
x	A variables	[−]
k	The heat coefficient of the heat-conveying liquid at specific temperature and pressure	[W/(m$^{2.\circ}$C)]
ΔT	The temperature difference of the heat-conveying liquid at the flow and return terminal	[°C]
ε_g	Emissivity of the globe	[−]
λ	The thermal conductivity of the material	[W/m °C]

Chapter 1

INTRODUCTION

1 Introduction

1.1 Background

Global warming is the most important issue of environmental challenge all over the world. The top priority is to minimize climate change by reducing greenhouse gas emissions. In addition, there is an increasing awareness on the importance of reducing carbon emissions in the world. Around 30-40% of all primary energy is used in buildings all over the world. Therefore, reducing energy consumption in buildings can help reduce carbon emissions significantly (UNEP, 2007).

China is the second largest country in the aspect of both energy production and consumption. The building sector accounts for nearly 20% of the total energy consumption in China. In the past 20 years, building energy consumption in China has increased at a rate of more than 10% every year (Siwei & Yu, 1993; GB50178-93, 1993; Lang, 2004; Li, 2008). It is important to improve the energy efficiency and to promote energy-saving technologies of buildings (Yang, et al., 2014; Chen, et al., 2008). Residential energy consumption is the second largest energy use in China. Additionally, residential building areas increase by two billion square meters every year. The residential energy consumption depends significantly on the climate of the regions in China (GB 50178-93, 1993; Jiang & Hu, 2006; Zhou, et al., 2010). There are rapid increase and continuous growth in the residential energy consumption, so that it is reasonable to separate China into several climatic zones (Yuan, et al., 2013; Zhang, 2004). Based on the national standard named “Standard of Climatic Regionalization”, generally, China is separated into five climatic zones (see Figure 1.1) (GB50178-93, 1993):

1. Severe Cold Zone

2. Cold Zone

3. Hot Summer and Cold Winter Zone

4. Hot summer and Warm Winter Zone

5. Mild Zone

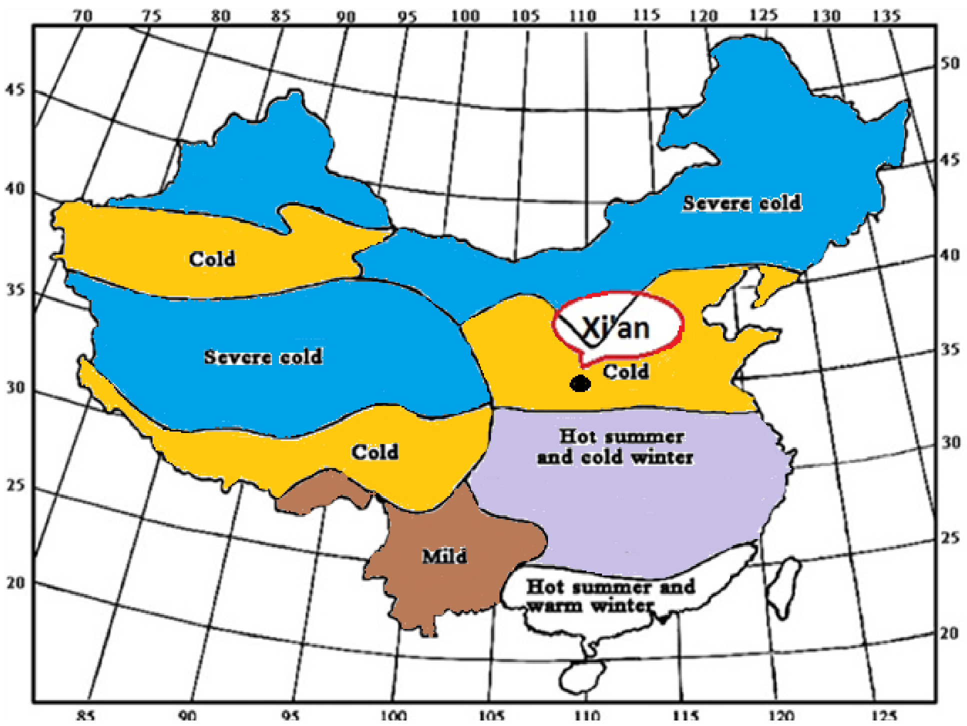


Figure 1.1 Five climatic zones of China

Table 1.1 Characteristics of climatic zones in China

Climatic Zone	**Number of days ≤5°C**	**Number of days ≥25°C**	**HVAC for Winter**	**HVAC for Summer**
Severe cold	≥145Days	--	Central Heating	Air-conditioning
Cold	145~90Days	≤80Days	Central Heating	Air-conditioning
Hot summer and cold winter	90~0Days	40~110Days	N/A	Air-conditioning
Hot summer and warm winter	--	100~200Days	N/A	Air-conditioning
Mild	90~0Days	--	N/A	Air- conditioning

Table 1.1 presents the characteristics and different requirements of HVAC systems for each climatic zone. In severe cold zone and cold zone, central heating in winter

and air-conditioning in summer is required. In hot summer and cold winter zone, air conditioning in summer is required (central heating is not required). In hot summer and warm winter zone, the major requirement is air conditioning, and few residential buildings are equipped with individual heating system (Lang, 2004).

The severe cold and cold zones (also regarded as **C**entral **H**eating **Z**ones) are defined as *"where the average daily outdoor temperature for any five successive days is lower than or equal to 5°C, for more than 90 days in a year*" (Siwei & Yu, 1993). The central heating zones account for approximately 70% of total national territory and account for approximately 45% of the total national energy consumption (Zhong, et al., 2009; Jiang & Yang, 2006). According to the official statistics from the Chinese Ministry of Construction, 45% of occupants living in urban areas have been provided with winter space heating (GB 50178-93, 1993; Jiang & Hu, 2006; Zhou, et al., 2010). Approximately two-thirds of urban residential buildings in the central heating zones are installed with centralized, hot-water radiator heating systems, however, residential hot water is not provided. The central heating system comprises constant water flow rate with the water temperature controlled by a heating substation (Document of World Bank, 2014; Yao, et al., 2005).

Analysis of urban residential energy use in central heating zone showed high levels of waste caused by space heating. The central heating systems run 24h per day continuously, and there are no individual heating control systems thus occupants can only open their windows/doors to adjust indoor thermal conditions (Xu, et al., 2009; Chen, et al., 2011). The central heating system consists of radiators that are traditional vertical single-pipe systems therefore it is hard to install the occupants' control systems and metering within the buildings (Document of World Bank, 2014). In the past, the heating costs in Chinese residential buildings were based on a flat payment rate per square meter of floor area of houses. Taking all this into consideration, in order to reduce energy consumption, the Chinese government adopted a new method of charging citizens for the heating service and payments. The newly-built residential buildings are required to have a variable-flow, two-pipe design and incorporate manual valves (i.e. Thermostatic Radiator Valves) and heat meters in radiator systems (Document of World Bank, 2014; Xu, et al., 2009).

In 1995, the Chinese government announced an energy conservation design standard JGJ26-95 in heating system for new residential buildings. According this standard, for a majority of residential buildings built before 1995 the heat transfer coefficients of external walls and windows are more than 1.6W/m^{2}K and 5.0W/m^{2}K, respectively (Yang, et al., 2012). These have since been improved due to the introduction of the 1995 standard by the government. In China, the most common heating system in old residential buildings is central heating systems without private control. In the 1995 design standard, heating control systems have been encouraged to be used in the central heating systems in new residential buildings.

In 1995, the national standard on building energy efficiency in China (JGJ 26-95) was updated with the new residential buildings standard (JGJ 26-2010) published in 2010. The new standard highly recommended that all new residential buildings install personal control of the heating system, such as Thermostatic Radiator Valves (TRVs), together with implementation of ‘pay for what you use’ tariffs. Additionally, the heat transfer coefficient of external walls was limited to 0.78W/m^{2}K and 2.70 W/m^{2}K for windows. As a consequence, improvements have been made in the building fabric insulation levels to help the construction of more energy efficient buildings.

It is thus very important to explore the influence of the upgraded standards on the heating energy consumption during winter periods in central heating zones in China. Thus in this research, Xi’an is chosen to be a representative city which has a typical cold and dry climate in winter. Based on the different standards, two types of space heating systems were defined: central heating without personal control systems and central heating with personal control and heat meter systems. In this research project, fourteen apartments using each type of heating system were monitored, and energy consumption and thermal comfort were evaluated. Moreover, it is important to evaluate the impact of different building design standards on the thermal and energy performance of buildings, through a comparison of various aspects (building construction, indoor thermal environment, occupant behaviour, thermal comfort and building energy consumption) of two types of residential buildings developed under different standards.

1.2 Aim and Objectives

Aim: For multi-storey residential buildings, to investigate the effect on heating consumption of moving to a ‘pay for what you use’ policy (capable of occupant control) compared to the existing flat rate payment based on floor area only (no occupant control).

The follow five objectives were identified to achieve the above aim.

Objectives:

1. To identify two sets of typical Chinese residential buildings; one set having an unmetered and uncontrolled heating system whilst the other set having control systems and heat meter devices as part of the heating system. To measure the indoor thermal conditions, heating energy consumption, occupant behaviour and thermal comfort in each set of residential buildings.
2. To identify the effect of the new control systems and payment methods on energy consumption in multi-storey residential buildings, and to compare the indoor thermal conditions, heating energy consumption, occupant behaviour and thermal comfort in each set of residential buildings.
3. Validate the simulated energy consumption using the real monitored energy use, and improving the modelling techniques using real measured variables
4. Through thermal modelling of stock, to estimate the saving in energy to be expected from a larger number of dwellings, together with issues of cost comparison(i.e. cost of metering and controls versus value of energy savings)
5. To make policy recommendations, based on the findings above.

1.3 Thesis Structure

This thesis has been divided into the following seven chapters:

- **Chapter 1. Introduction:** background of this thesis, aims and objectives of the project.
- **Chapter 2. Literature Review:** thorough review of relevant literature, the aspects of energy consumption all over the world and residential buildings in China. Furthermore, discussion of the reform and implementation of heating and bill system in newly built residential buildings. Review of standards and regulations is conducted of how they affect the heating energy use during heating periods. Additionally, existing heating control systems related to occupant behaviour and thermal comfort is presented.
- **Chapter 3. Methodology:** the experimental and simulation methods used to investigate the effects of the new building standard on heating energy consumption are explained and justified. Additionally, the method of analysis for behaviour and thermal comfort is also presented.
- **Chapter 4. Results:** Comparisons and analysis of indoor thermal environment, occupant behaviour, heating cost and heating energy consumption results for both new and old residential buildings.
- **Chapter 5. Results:** The modelling technique and simulation results are verified with monitored data.
- **Chapter 6. Results:** Comparison of thermal comfort in new and old apartments is presented and further evaluation is explored
- **Chapter 7. Conclusions:** Conclusion of the entire project is discussed, contribution of knowledge is highlighted and recommendations of future work are presented.

Figure 1.2 provides the breakdown of thesis into chapters and states their corresponding objectives.

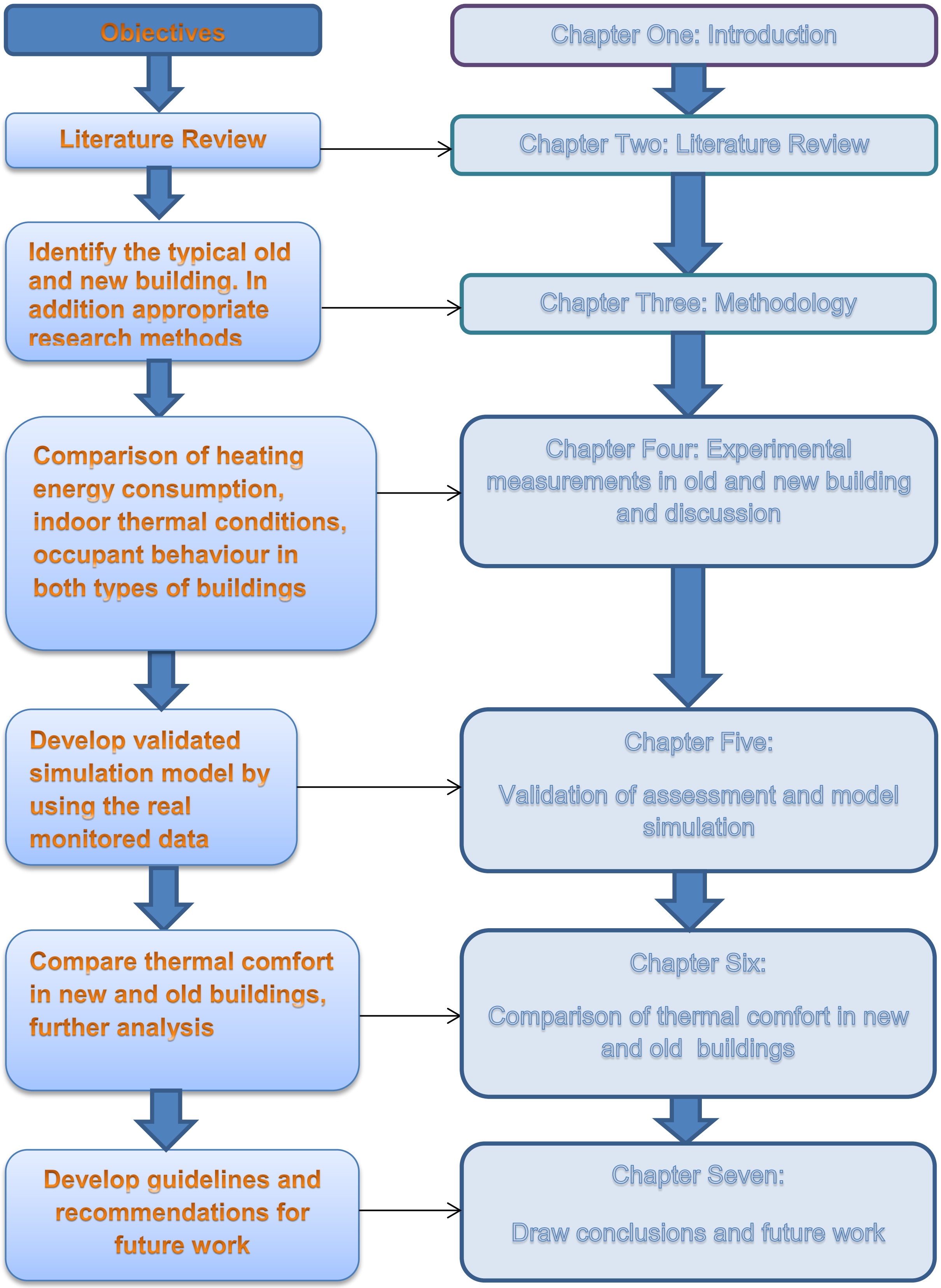


Figure 1.2 Struture of Thesis

Chapter 2

LITERATURE REVIEW

2 Literature review

2.1 Introduction

This chapter presents a review of relevant academic research to this thesis. It reviews the current situation of building energy consumption all over the world, energy used in Chinese residential buildings, Chinese government policy, occupant behaviour and thermal comfort in Chinese residential buildings. The role of occupants in the energy consumption for the residential building will be discussed. The influence of potential factors on occupants' heating behaviour will be identified. In addition, thermal comfort related to research area of this thesis were reviewed.

The aim of this chapter is to describe the reform and implementation of heating and bill system has been recommended into new built residential buildings in Central Heating Zone. So that it is important to identify how the new standard might affect the energy consumption, occupant behaviour and thermal comfort in Chinese residential buildings. Meanwhile, to evaluate the new residential building standards and regulations how affect the heating energy use during heating periods. Further, is to identify the existing heating control systems related to occupant behaviour.

2.2 Building energy consumption

2.2.1 Worldwide building energy consumption

Energy consumption has become the one of largest issue in the modern society. Buildings play an important role on energy consumption in the world, accounting for 40% of total end use of global energy consumption (Ibn-Mohammed, et al., 2013). Figure 2.1 shows that the total end use of energy consumption consists of five parts: industry, residential, commercial, transport and other sectors. Residential and commercial sectors account for more than 35.9% of final energy use all over the world. Furthermore, the residential sector is one of major global energy consumer, which is globally accounting for 27.1% of the total energy use (Laustsen, 2008).

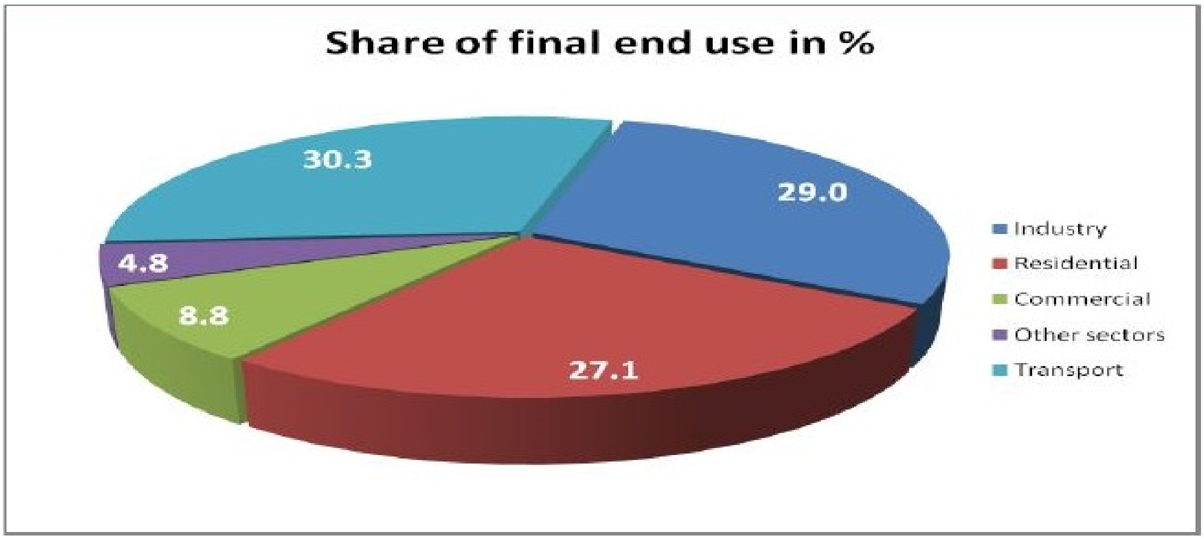


Figure 2.1 Energy consumption in different sectors in the world

(Laustsen, 2008)

A large part of energy consumption in residential sector account for more than 35% in developing countries, it is clearly shown in Figure 2.2 and it illustrates that the percentage of building energy consumption and building sectors in different countries in the world. China is one of largest developing countries in the world. The percentage of energy consumption in residential sector in developed countries, representing 20% of total consumption (Nejat, et al., 2015; Yau & Hasbi, 2013).

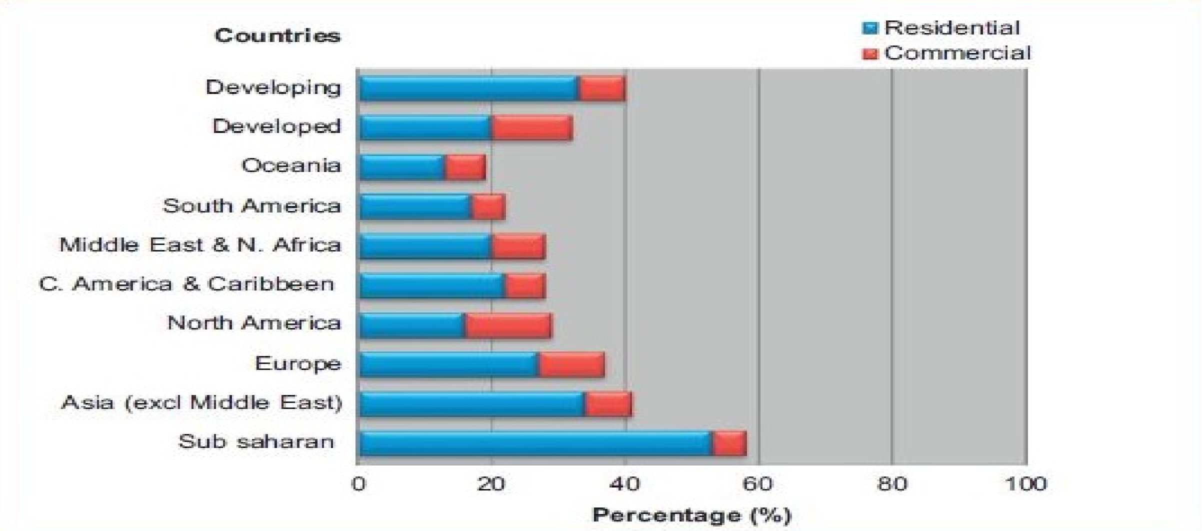


Figure 2.2 Percentage of global energy consumption in both residential and commercial buildings

(Yau & Hasbi, 2013)

Energy used in services sectors can be divided into four main parts: space and water heating, lighting, cooking, and appliances (Xing, et al., 2011). As show in Figure 2.3, space heating is accountable for the greatest fraction of total energy use in residential buildings. There is a clear trend that fraction of energy consumption in residential buildings in individual countries, it also shows that the issues on comparison and normalisation (Laustsen, 2008).

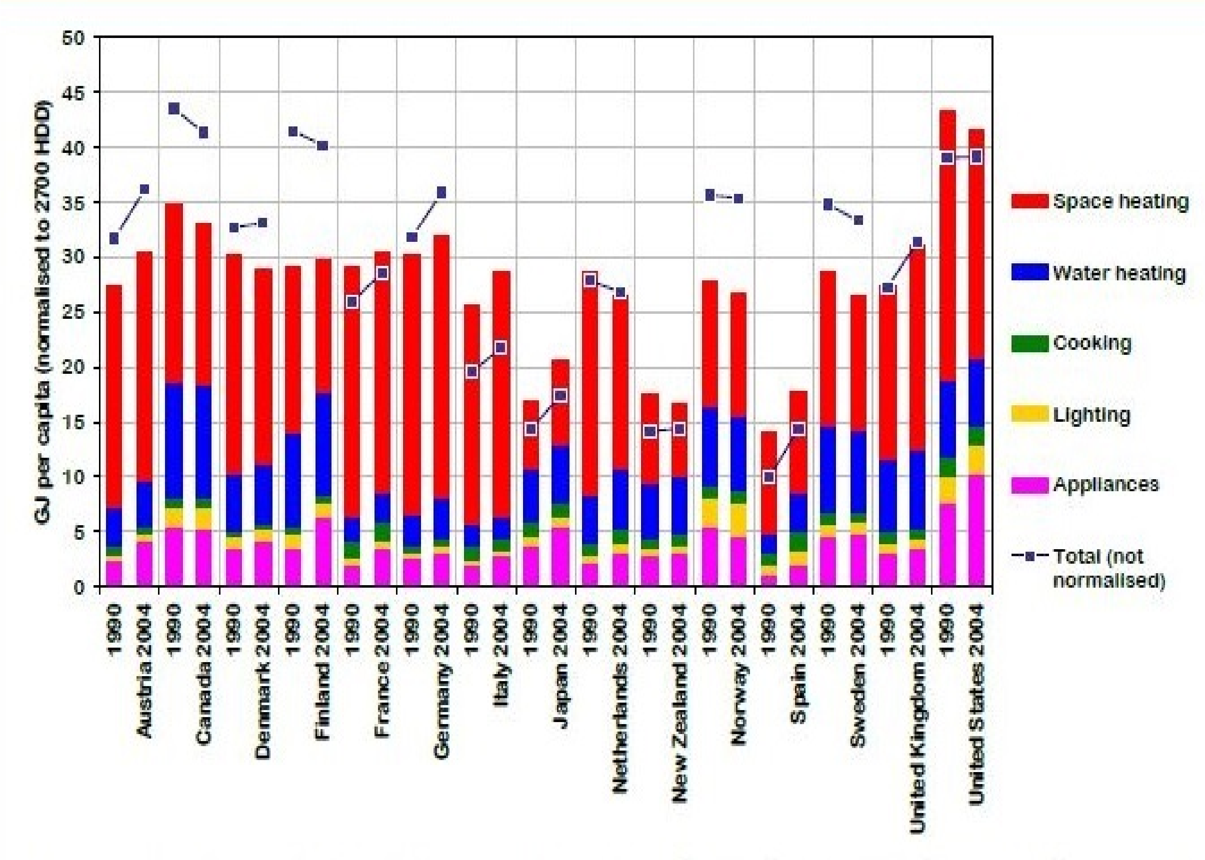


Figure 2.3 Energy consumption in the residential buildings in select IEA countries (Laustsen, 2008)

In 2010, the global energy use in residential sector represents 2074Mtoe, since 2000 the energy consumption has increased by 14%. Related to this, the two main energy resources used in residential buildings are fossil fuels and renewables. As show in Figure 2.4 electricity used in residential buildings increased by 4%, while biomass has fallen to 39.7 % between 2000 and 2010. It is illustrates that traditional biomass is main sources of energy use in residential buildings and is mostly use in developing and developed countries (Nejat, et al., 2015).

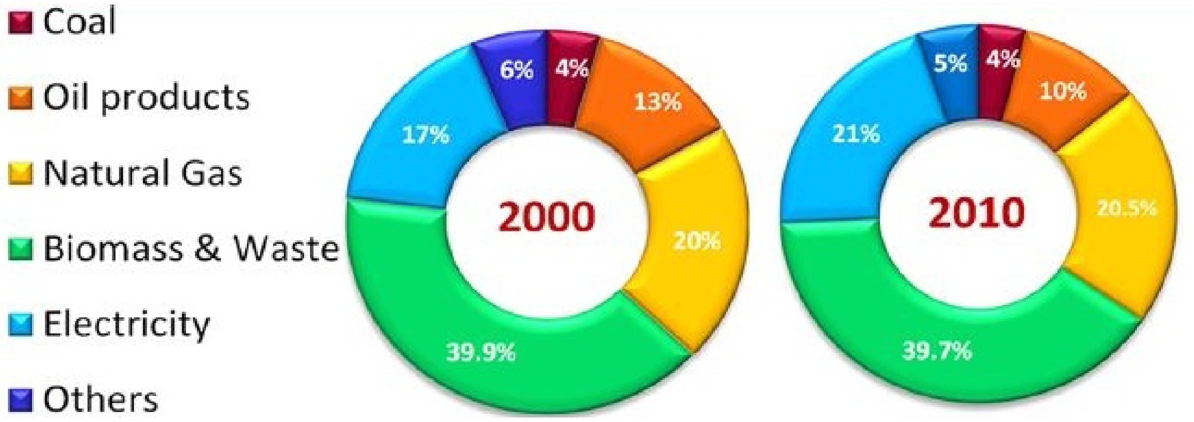


Figure 2.4 Different energy resources used in the residential buildings in 2000 and 2010 in the world

(Nejat, et al., 2015)

Climate change is anticipated to have significant effect on building energy requirement. In particular, future energy demand of buildings has remarkable effect on global warming. Thus, building plays an important role on global warming (Yau & Hasbi, 2013). In 2011, residential buildings account for the fourth largest section of global CO_2 emissions, it directly account for 6% and indirectly account for 11% of CO_2 emissions sector in the world (Nejat, et al., 2015).

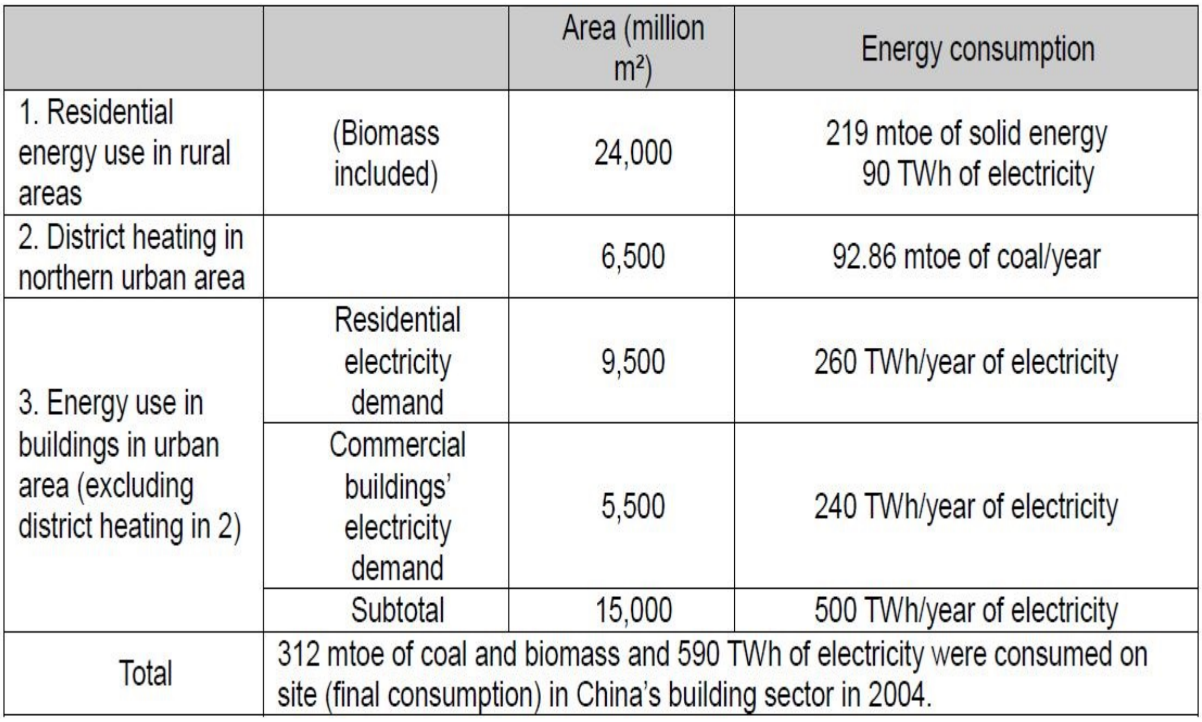
2.2.2 Energy consumption by building sector in China

China is second-largest global energy market in the world. The total end use of energy consumption in China can be divided into five parts: industry, transport, residential, commercial, other sectors. In 2011, the energy use in residential sector in China represents more than 350Mtoe, since 2000 the energy consumption has increased by approximately 20%. The electricity used in China increased rapidly, while biomass has increased to more than 270Mtoe of total final energy use between period 2000 and 2010. It is estimated that the urbanization rate is predicted to increase to 55% in 2020 and 58% in 2030 (Nejat, et al., 2015; Tonooka, et al., 2005). More than two billion m^2 of buildings are constructed each year in China. CO_2 emissions in building sector account for 18% of total emissions in China. Relate to this, buildings have become a significantly growing energy consumption sector. The Ministry of Housing and Urban-Rural Development of China (MOHURD) stated that in 2012, building energy consumption in China account for 27.5% of total energy consumption (Zhang, et al., 2015). Building sector in China is one of largest growing part of energy use both in construction stage and in the operation stage lead to large scale environmental pollution (Du, et al., 2004).

As shown in Figure 2.5, the significant increase of energy consumption in building materials production correlation with enormous increase of floor areas of buildings under construction. Table 2.1 lists general energy use in building sector in China in 2004. Energy use in buildings in central heating zone represents 92.86Mtoe of coal per year (Li, 2008).

Figure 2.5 Energy for building materials production from 2001 to 2013 in China (Zhang, et al., 2015)

Table 2.1 Overview of energy use in building sector in China



		Area (million m^2)	Energy consumption
1. Residential energy use in rural areas	(Biomass included)	24,000	219 mtoe of solid energy 90 TWh of electricity
2. District heating in northern urban area		6,500	92.86 mtoe of coal/year
3. Energy use in buildings in urban area (excluding district heating in 2)	Residential electricity demand	9,500	260 TWh/year of electricity
	Commercial buildings' electricity demand	5,500	240 TWh/year of electricity
	Subtotal	15,000	500 TWh/year of electricity
Total	312 mtoe of coal and biomass and 590 TWh of electricity were consumed on site (final consumption) in China's building sector in 2004.		

Sources: (Jiang, 2007),'Current status of energy use in buildings in China', in 2007 Annual report on China building energy efficiency, Tsinghua University, China Energy Statistical Yearbook 2004.

2.2.3 Energy consumption by residential building sector in China

2.2.3.1 Building classification in China

According to the statistics provided by MOHURD, existing buildings in urban areas of China can be classified as six different types, is clearly given in Figure 2.6 and a great number of them are residential buildings, which account for a proportion of 53.8% (Siwei & Yu, 1993).

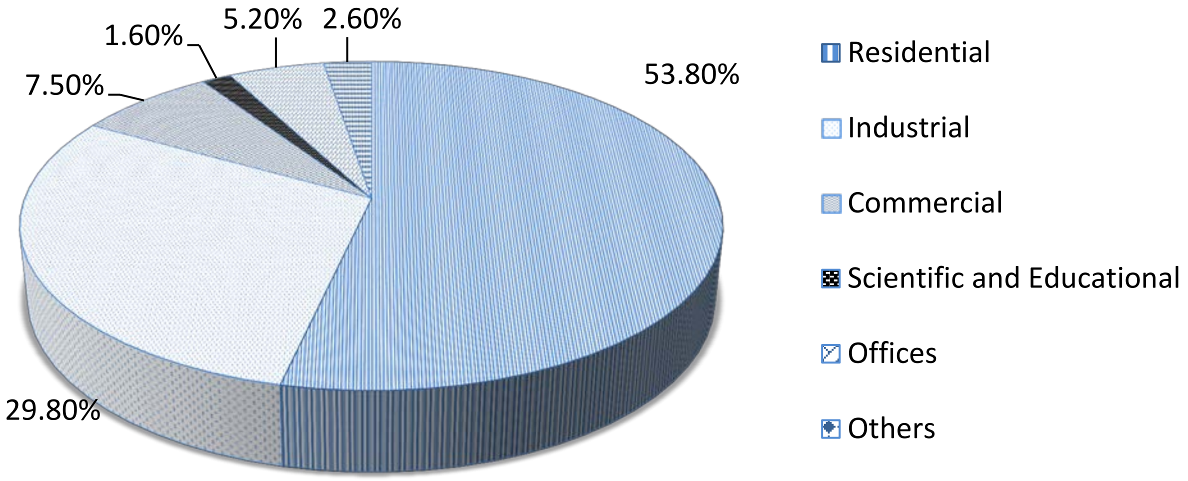


Figure 2.6 Amount of existing urban floor area in the Central Heating Zone divided into building sectors

Source: The Ministry of Housing and Urban–Rural Development **(Siwei & Yu, 1993)**

2.2.3.2 The overview of residential building sector in China

In addition, the Chinese residential buildings can be further separated into four main categories (GB 50093, 2003): Low-rise buildings (1-3 stories), multi-story buildings (4-6 stories), middle to high-rise buildings (7-9 stories) and high-rise buildings have greater than 10 stories. In these categories, the most of existing common buildings are multi-story buildings in urban areas (Siwei & Yu, 1993). However, the residential buildings in rural areas is different, the rural villa is self-built (one or two stories houses in rural area regarded as old traditional buildings).

Currently, there is a great number of residential buildings will be built newly 1.6 to 2 billion m^2 every year. There are huge amount of new residential buildings have been built within past 10 years, it account for around 60% of all residential buildings. Additionally, there are also about 35% residential buildings are aged between 10-30 years and there are about 5% buildings are older than 30 years (see Fig 2.7) (Siwei & Yu, 1993; F.X.Tu & A.X.Li, 1991)

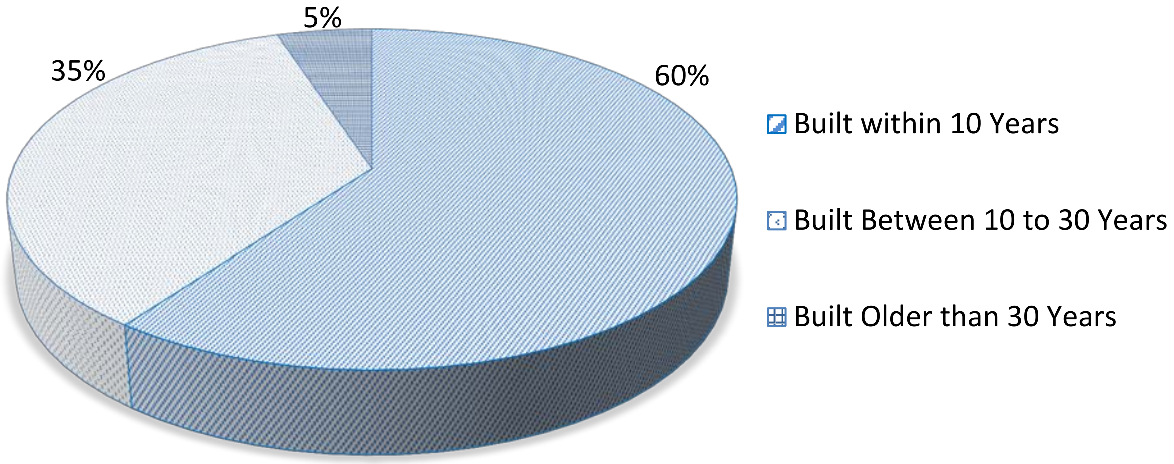


Figure 2.7 The percentage of age of built residential building in China

(Siwei & Yu, 1993)

2.2.3.3 The energy use in residential building sector in China

Heating account for largest section of energy use in residential buildings in China, it directly accounts for 59%, and residential appliances account for 21%. Lighting account for 9% and cooking account for 7%. The lowest energy use is other uses, account for 4% (Zhou, et al., 2010) (see Fig 2.8).

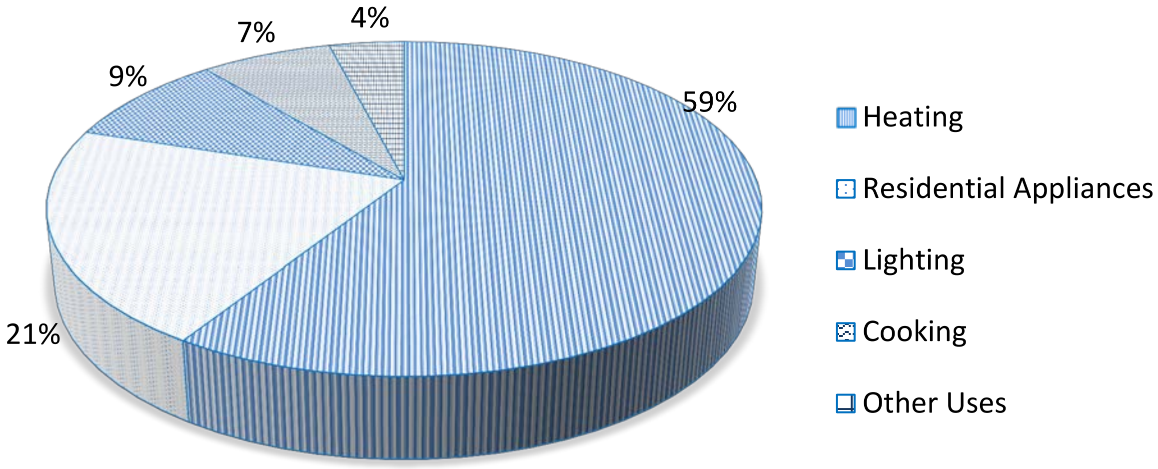


Figure 2.8 Residential energy consumption by end use in China

(Zhou, et al., 2010)

As mentioned above, the most existing buildings in China are residential buildings accounting 53.8%. Meanwhile, most of existing common residential buildings are multi-stories. The multi-stores residential buildings account for a great large number of heating energy consumption in China. The energy use in the household sector in Chinese residential building includes space and water heating, cooling, lighting, cooking and the use of appliances. It is important to emphasize that the space heating is the biggest source of energy consumption, which account for 59% of residential energy consumption (Fig 2.8). Energy demand in residential buildings has become an important factor affecting economic development in urbanization. With the rapid development of standards of living, energy consumption in Chinese residential sector will increase greatly (Li, 2008; Chen, et al., 2008).

Chen et al indicated that the dwelling size and number of occupants are two key contributors to rise in the energy demand for heating in residential buildings (Chen, et al., 2013; IEA, 2008). A review study conducted by Chen et al. of field study in Shanghai of China showed that how the various potential variables result in difference of annual energy consumptions characteristics between old and new residential buildings. They analysed the factors that affect the energy consumption between old and new dwellings. The results indicated that the average annual energy consumption quantities in old buildings are always higher than that in new ones. However, there are not significate differences of the building envelop between old and new dwellings. It also can be explained by different climatic zone and different building design standards (Chen, et al., 2009).

Therefore, it is important to evaluate the old and new residential energy consumption in multi-story residential buildings in China. Furthermore, the energy uses relating to residential buildings have been required considerable reduction. And the government have pay more attention on reduce the residential energy use in China and consequently this work focus on the energy consumption in both new and old multi-stores residential buildings in CHZ.

2.3 Building energy codes in China

2.3.1 Overview of building energy codes in China

Several standards, incentive policies and building codes were issued, in order to promote energy efficiency in Chinese buildings. Building code development pays more attention on residential buildings than public buildings (Shui, et al., 2009). In 1998, the Chinese government established the Energy Conservation Law (ECL), aiming to encourage energy conservation activities and improve energy efficiency. In addition, ECL is aiming to protect the environment and achieve sustainable development. In the ECL, the use of renewable energy in real applications is emphasised (ECL, 1997). In order to improve energy conservation, appropriate energy conservation standards for buildings were issued and implemented by Chinese government (Fig 2.9). It shows that the overall building standards for design and acceptance of codes in three main climate zones.

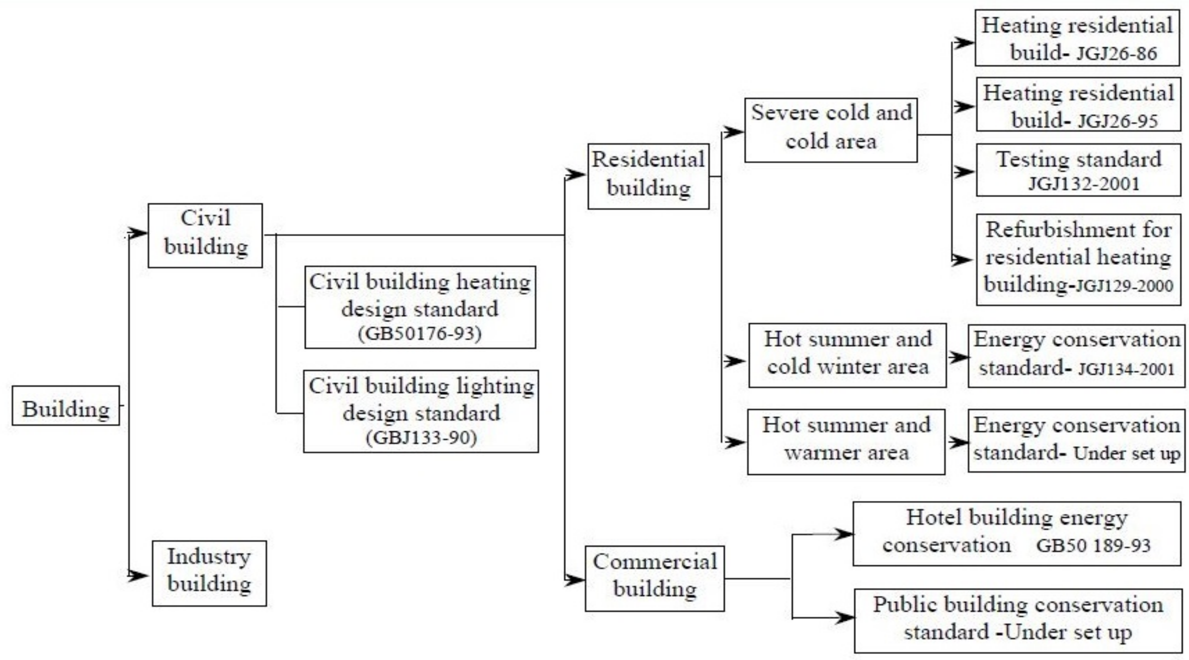


Figure 2.9 Overview frame of building energy codes in the built environment

(Yao, et al., 2005)

Source: Wu Y. 'Chinese building energy conservation: existing situation, problems and policy', presentation on the International Conference on Sustainable Development in Building and Environment, Chongqing, China 24th–27th 2003.

In order to improve building energy efficiency, MOHURD set up several goals and building energy standards. A Green Building Evaluation Standard in China was first introduced from MOHURD, which proposed the target of energy saving of throughout the life cycle of residential and public buildings. This standard relevant to land savings and outdoor environment, energy saving, water saving, material saving, indoor environmental quality, operations and managements.

2.3.2 Energy conservation standards for residential building in China

According to extensive geographic zones and climatic conditions in China, heating energy consumption has improved more and more in Chinese residential buildings. The purpose of energy saving is to set fundamental standards to control energy consumption from energy source. Therefore, energy conservation should be considered as a focus of China's energy policies, and relevant industrial standards, rules and regulations related to energy conservation should constantly be developed and improved (Yang, et al., 2014). In order to reduce the energy use and promote energy efficiency in China, Chinese government has started to concern the energy efficiency of buildings in China in early 1980s. With the support of the Ministry of Construction (MOC), an energy efficiency code for residential buildings in the China was first introduced in 1986, which proposed the target of 30% energy saving. This is first publication of the Energy Conservation Standards for Heated Residential Buildings in CHZ in China (revised in 1995, implemented in 1996) (Lee & Chen, 2008; Lang, 2004; Shui & Li, 2012; Glicksman, et al., 2001). However, in this regulation, the heating of residential buildings was not commonly considered.

Heating energy consumption needs to be reduced for the CHZ area during the winter season. Inappropriate design and deficient policy in centralized heating systems result in heat losses in buildings. The heating system without personal control in residential buildings and people only can open window or door when the room overheated during heating period. Overheating in rooms generally result in occupants to open the window (Li, 2008). Thus, in July 1996, "Energy conservation design standard for new heating residential buildings, JGJ26-95" started to be implemented. The benchmark of this standard is based on the heating energy consumption in typical residential buildings in beginning of 80's, which requires that the new residential buildings should save 50% heating energy consumption (30% from insulation and 20% from boiler & pipeline) compared with old ones (Jiao & Wang, 2007). The national standard on building energy efficiency in China (JGJ26-95) was updated with the new residential buildings standard (JGJ26-2010) published in 2010. The new standard highly recommended that all new residential buildings install personal control of the heating system, such as Thermostatic Radiator Valves (TRVs), together with implementation of 'pay for what you use' tariffs. As a consequence, improvements have been made in the building fabric insulation levels to help the construction of more energy efficient buildings. The details of two standards for residential buildings in CHZ area in China show as follow:

The standard "Energy conservation design for new residential buildings" (JGJ26-95, 1996)

- Concerned with relevant effective measure in order to reduce the energy consumption and improve the thermal environment in residential buildings. Since 1996 the newly built residential buildings operated by central heating system and relevant procedures have been issued strictly by standards and codes in China.
- In the new standard, the heating control systems have been encouraged into design pattern in the new residential buildings.
- A majority of residential buildings built before 1995 the heat transfer coefficients of external walls and windows are more than 1.6W/m^{2}K and 5.0W/m^{2}K, respectively. However, compared with the western industrialised countries building insulation is still not effective and there is room for improvement in Chinese residential buildings.
- In this standard, recommend the index of heat consumption range from 20-22.7W/m^2 of floor area. Meanwhile, the index of coal consumption for heating residential buildings range from 8.7–29.4 kg/m. The building shape coefficient and ratio of window to wall have been issued and target value presented as well in the standard (Yao, et al., 2005)

“Design Standard for Energy Efficiency of Residential Buildings in Sever Cold and Cold Zones” (JGJ26-2010, 2010)

- Mandatory requirement of the heating system pattern, it should implement household-based heat metering and install the Thermostatic Radiator Valves (TRVs) in each radiators.
- The new standard is beneficial to energy saving and implementation.
- Furthermore according to the new standard for energy efficiency of residential constructions applied in 2010, the heat transfer coefficient of external walls is 0.78W/m^{2}K and 2.70 W/m^{2}K for windows.

The standard (JGJ129-2000, 2001) of technical specification for energy conservation renovation of existing heating in residential buildings developed by Beijing Zhongjian Institute of Building Design under the Ministry of Construction in October 2000. JGJ 129–2000 indicated the renovation of existing residential buildings with central heating systems which are located in CHZ. Meanwhile, the specification indicated that energy refurbishment rule of the existing residential building envelop with different heating systems are issued as well (Siwei & Yu, 1993; Yao, et al., 2005).

2.4 Heating energy consumption in Chinese residential buildings

Residential buildings in the CHZ are result from a large percentage of heating energy use. In 2005, central heating account for 18% of total energy used by residential buildings, while 3% of total energy used by commercial buildings (Eom, et al., 2012; Chang, et al., 2013). In addition, from 2004 to 2024, the residential building in CHZ is predicted to grow from 4 billion m^2 to 11 billion m^2. According to the official statistics from the Ministry of Construction of China, more than 250million occupants live in urban areas with district heating during the winter season. Approximately 45% of buildings heated by central heating plants that fuelled by coal in CHZ areas (Li, et al., 2009). The major heat source systems include coal-fires boiler, combines heat and power generation (Zhang, et al., 2015). Furthermore, coal use is most common in space heating and it increasing fast. As show in Figure 2.10 (Zhou, et al., 2010), coal is a largest fuel use in residential buildings affecting final energy consumption. Thus, space heating is key contributor to immense energy waste and serious problem with air pollution during heating season in winter in China (Meyer & Kalkum, 2008). Heating energy consumption increasing rapidly correlated to growth of household energy end use. The energy consumption of space heating has drawn increasing attention from Chinese government. The mandatory building codes (JGJ26-95, 1996; JGJ26-2010, 2010) for space heating energy efficiency in residential building play an important role to improving the efficiency of heating needs (IEA, 2008).

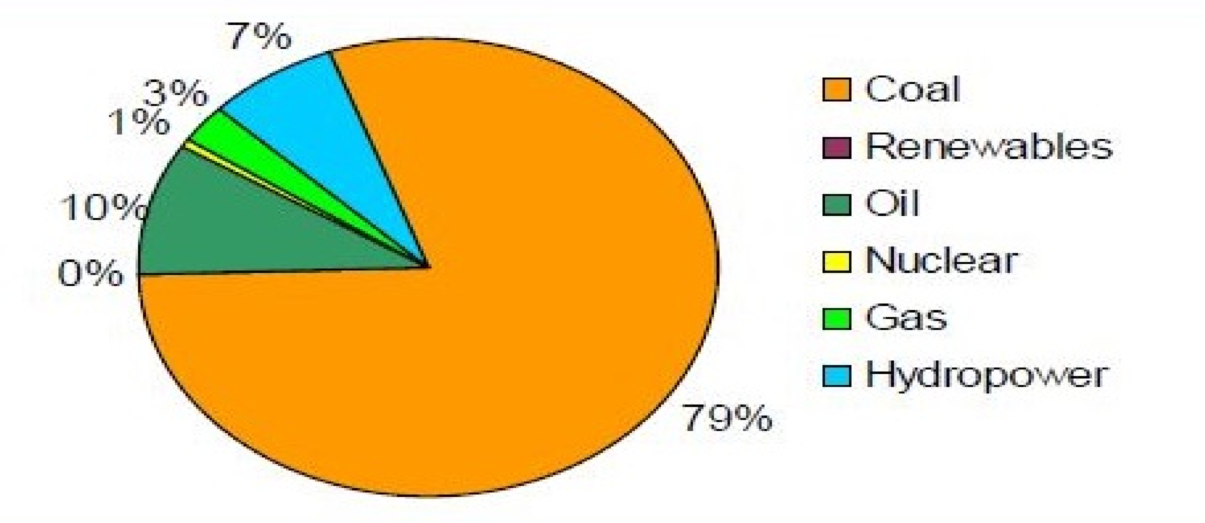


Figure 2.10 Energy consumption in residential buildings by fuel in China

(Zhou, et al., 2010)

2.4.1 Existing Heating Systems in Chinese residential buildings

Nowadays, in typical residential buildings, most common heating system is equipped by the centralized, hot-water radiator heating systems in CHZ. In addition, there are two-thirds of urban residential buildings in CHZ that are heated by centralized systems. First, central heating system is common heat supply system in Chinese cities. The principle of centralized heating is urban heating network, district heating networks. In the central heating system, hot water is generated by a boiler or cogeneration plant, meanwhile, all cogeneration plants burn coal and water flow through to radiators in the living spaces through a network (Siwei & Yu, 1993). As show in Figure 2.11, the sample of central heating system is water flow through with constant speed via pipe network. The traditional vertical single heating pipe with radiators are sequentially connected from top floor to bottom floor (World Bank, 2004). The changes of water temperature are operated by heat source or substation, in accordance with outdoor temperature is too high. The occupants cannot adjust their heating, and indoor temperatures are often too high leading to people opening their windows, resulting in additional heat waste. Compared to western developed countries, the systems do not have any of the energy control equipment such as thermostats (ERI, 2004; MOC, 2008).

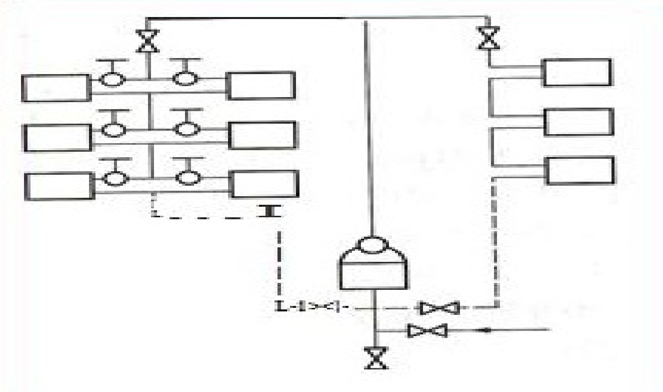


Figure 2.11 Single pipe with radiators of central heating system

Second heating system is household gas-boiler heating has been partly developed and used in new residential buildings, the gas boiler is main component and is normally install in kitchen or balcony. The heating time can be set by occupants and each room temperature can be adjusted within a range. However, it is not popular in most residential buildings in Central Heating Zone. Another heating system is home central air-conditioning system operated by thermostat. This system interaction with high quality and high comfort, and the temperature can be adjusted by occupants. However, this system is commonly used in Villa which has higher operating costs. Finally, another development of heating system is the underfloor heating system. The underfloor heating systems has been used in some newly buildings. It is heats room's floor structure which is in turn warms room itself. Compared with other heating system, floor heating system is more energy efficient.

2.4.2 Reform of heating payment system in China

2.4.2.1 Existing heat billing and pricing systems

The centralization heating is commonly used in residential buildings in China and it comprised uncontrolled heating system with payment based on floor areas of occupants home. Space heating catalysed tremendous energy wastes in residential buildings. In order to improve the heating energy efficiency in new residential buildings according to new standard, the individual heating control systems were installed and payments of heating are relied on metered consumption in each apartment. It is important to provide incentives to occupants to use heat efficiently and to control their heat consumption during heating season in winter. The new technical adjustments are required to install so as to achieve occupants have ability to adjust the flow of hot water in each radiator. In addition, the water flow rate passing through each radiator is controlled by a thermostatic valve. Occupants via adjust thermostatic radiator in order to control heat consumption and achieve to comfort indoor condition. Therefore, an energy-saving and comfortable environment could be created (Xu, et al., 2009). These policy changes should greatly enhance consumer awareness of the cost of heating energy and the value of energy savings and promote energy efficiency in buildings as well as strengthening the Chinese economy (World Bank, 2004; Meyer & Kalkum, 2008; Yao, et al., 2005).

As mention above, heat bills are calculated based on prices per square meter of heated areas in old buildings and it lead to enormous energy waste. Heat tariff is set by local government in each province for many years. During the winter, the heating price range from 5.0yuan/m^2 to 5.8yuan/m^2 in city of Xi'an of Shaanxi provinces in Central Heating Zone. In addition, the average heating period range from 120 to 160 days during winter season in CHZ (XASRLGS, 2012). For instance, in an old residential building without control system, the floor areas of apartment is 100m^2, annual heating payment is 2320yuan per household in city of Xi'an, occupant pays once at beginning of heating season.

In contrast, heat metering bill are calculated based on measurement of heat meter in each household according to actual energy use. So that new heat bill payment system allow occupants control their energy use and provide incentives for them to use heat efficiently. The effect of improvement can be evaluated by new heat metering bill system compared with old one. The reform of heat price with measurement of heat meter is 0.16yuan/kWh. The reform of tariffs can be divided into two parts: basic heat payment bill and actual metered energy use bill. The equation show as follow (XASRLGS, 2012):

Total energy price=basic energy price [1.74yuan (5.8yuan/m^2 permonth×30%) × floor areas×4] + actual metered energy use bill [(0.16yuan/kwh × 70% × total metered of kWh)]

As a consequence, the reform of heating bill system might lead to different occupant behaviour which have significant effect on economic effectiveness and energy saving. The implications of cost of heating bill reform were discussed in following analysis chapters.

2.4.2.2 Promoting insulation level in Chinese residential buildings

It is important to enhance building envelope’s energy performance by means of surface insulation, the application of innovative materials, design optimisation and enhanced natural ventilation, as well as the behaviour control of inhabitants and end users (Li & Shui, 2015). Thermal insulation of buildings defined as functions by slowing the rate of heat transfer from warm room air to cold outside air during heating season (Susan & Mary, 1992). Most of old residential buildings are not insulated in both CHZ and other zones in China. Well-insulated building not only can improve occupants’ environmental comfort, but also reduce heating energy consumption related to greenhouse gas emissions. Therefore building standards mandatory require improving the insulation in residential buildings in recent year. The insulation levels are classified as different requirement in different climatic zone in China (Liu & Liu, 2011). The existing studies in residential sector in China largely focused on measures to improve building energy efficiency by fabric insulation (Cai, et al., 2009; Li & Colombier, 2009; Liang, et al., 2007; Ouyang, et al., 2011; Liu & Liu, 2011). Yoshino et al. investigated the indoor thermal environment of residential buildings in nine cities during summer and winter, in order to evaluated the thermal comfort and predict the residential energy consumption for space heating and cooling, it also notes that the thermal insulation and airtightness are important factors impact on the energy consumption for residential building in Beijing (Yoshino, et al., 2006). Liu opines that the effectiveness of insulation level for residential and commercial buildings, in addition, the better insulated in new buildings lead to the more energy saving and could save money (Liu & Liu, 2011).

Meanwhile, further studies in other countries have suggested the insulation levels impact on heating energy consumption. The study of Schuler (Schuler, et al., 2000) described how insulation standards might be considered as an important determination in demand of space heating for household. The work described in the paper of Haas et al, confirmed that the impact of residential house insulation on the energy demand for space heating (Haas, et al., 1998). As a previous study(Leth-Petersen & Togeby, 2001) using technical characteristics method in space heating energy consumption of Danish apartment blocks has been analysed, and it indicated that the dwelling insulation relevant for the energy efficiency of space heating. The simulation model was calibrated by using the measured data. However, the one of most important challenges is unpredicted human behaviour. For instance, the database schedules of occupancies and activities were inserted into energy simulation models to emulate the internal loads, however, the actual usage of building changes on a daily basis (Maile, et al., 2007). Therefore, it is worth to take into account the importance of occupant behaviour in residential buildings, shows following section 2.5.

2.5 Occupant behaviour

2.5.1 Occupants' behaviour related to heating energy consumption

Through review of previous studies, there is a definite possibility that the occupant behaviour have a significant impact on the energy consumption and the indoor environment. The occupants interactions with building controls can be regard as opening of windows, adjustments of heating set-points, turning lights on or off, using solar shading and turning air conditioning on or off. Occupants use building controls in order to offer comfortable indoor conditions which may affect the energy consumption. Consider that the various in buildings' control system could influence on the different energy performance of the buildings. It seems that the occupants' different behaviours have large effect on the heating energy consumption (Fabi, et al., 2012).

Several studies have used questionnaire surveys and measurements to investigate the determinants for energy consumption for heating during winter season. Park and Kim carried out a field questionnaire survey of occupants' behaviour and measurements of energy consumption in 139 apartments in Seoul in 2007, and they found that total heating energy consumption was affected strongly by indoor air quality correlation with occupants' ventilation behaviour. In their survey, the indoor air temperature can be controlled by thermostat in each apartment (Park & Kim, 2012).

Al-Mumin et al investigated the occupant behaviour and activity pattern which affect the energy consumption in 30 households of Kuwaiti and found that occupants prefer cooler indoor temperature by adjusting thermostat, whilst the lifestyle of occupant impact on annual energy consumption (Al-Mumin, et al., 2003). Indeed, many pervious research have found that the high correlation between energy consumption and occupant behaviour in buildings.

The significant influence of occupant behaviour on quantitates of heating energy use in house in Netherlands has been identified by Santin et al. In this study, results show that dwelling with higher heating energy use largely affected by higher heating set point by occupants (Santin, et al., 2009). In Austria, Haas et al performed a field study in 400 households and monitored energy demand of space heating. It indicated that strong relationship between heating energy demand and indoor air temperature due to occupants' actual demand. Consequently, the effects of occupant behaviour play an important role on improving energy efficiency in dwellings (Haas, et al., 1998).

The type and size of dwelling, the use of air conditioning system or control of heating systems for set point indoor temperature, the age of occupant, family size, household income and ownership of dwellings affect energy use for heating. The heating energy end use caused by the household in order to alter and achieve the heat comfort.

These findings were also suggested by Sardianou conducted study in Greek houses in 2003. It is implying that the socioeconomic status has effect on behaviour pattern. The above results of these studies indicated that the occupants' different behaviours have significant impact on the energy consumption of buildings (Santin, et al., 2009; Andersen, 2009; Sardianou, 2008).

Emery and Kippenhan carried out a longitudinal field measurement of space heating energy use and investigation of occupant behaviour during winter in new and old residential homes in USA. In their survey, the thermostat setting, the window/door operations and energy consumption were monitored in both types of houses. The high correlations between less heating energy use and better insulated new house employ with new code. In addition, they also observed that energy use in occupied old house is higher than that in unoccupied old one (Emery & Kippenhan, 2006).

2.5.1.1 Determinant factors for residential occupant behaviour

Consider that many studies have identified that a high correlation between the motivation of the building control and the occupant behaviour, it seems that the occupants' different behaviours have effect largely on energy performance in residential buildings. As well as the variations of individual resident behaviour may result in significant variations in energy consumption of buildings. Previous studies suggested that occupant behaviour can be caused by both internal factors and external factors. For the field of social area, human behaviour is relative to the internal or individual factors noticed by Schweiker, for example preference, attitudes, cultural background etc. In contrast, external factors include such as the air temperature, wind speed and building patterns for instance the ownership, available heating devices (Andersen, et al., 2009; Schweiker, 2010). Meanwhile numbers of studies concerning external factors have increased in the last years Nicol, 2001) (Haldi & Robinson, 2009; Andersen, et al., 2009; Nicol, 2001).

Several studies have used questionnaire surveys to investigate the determinants for residential energy use behaviour. It is no doubt that the many determinants impact on residential energy use behaviour. Sun and Feng have investigated a survey 1376 residents was carried out in Dalian, a coastal city in the northeast of China based on this method and found that variables such as the size of family, age of the resident, psychological, family and contextual factors impact on residential energy use behaviour. Furthermore, the results show that residential energy behaviour, attitudes or concerns towards energy problems are considered to be the most significant influencing factor. In addition, it have been suggested that it is important to consider the residents' attitude towards energy problems by improving education and publicity. As a consequence, it is worth to improve the awareness and action of occupant by using an economic instrument (Sun & Feng, 2011). Based on a field study and measurement for winter carried out by Schweiker and Shukuya in Japan determined that the residents use heating system are influenced by the individual experience and attitude more than that influencing by external conditions (Schweiker & Shukuya, 2009).

Stephenson et al pointed out the personal criterion of psychological variables can be considered as an important factor impact on residential energy behaviour (Stephenson, et al., 2010). As study conducted by Ameli and Brandt, they pointed that residents' habit to invest in clean energy technologies mainly depend on the home ownership, income, social context and households' information. It has been advised that ownership and income play relevant role in technology adoption (Ameli & Brandt, 2014). Furthermore, in respective of some other studies have demonstrated some social contextual or socio-demographics variables influence on the residential energy use behaviour. It is important to combine the individual and contractual factors into energy use behaviour. Personal factors can be regarded as attitudes, values, norms and habits. It interacted to contextual factors, can be regarded as physical infrastructure, technical facilities, availability of products, special product characteristics, income and material growth (Steg, 2008).

In Canada, Parker et al carried out an analysis of occupant behaviour for residential energy use can be related to variations of household characteristics. The study was investigated from 432 households from September 2000 to August 2001. It was found that higher income households consumed more energy than lower income households, in particular, family with children present more action to adjust heating thermostat than other type of family without children (Parker, et al., 2005). Following this study performed by Abrahamse and Steg investigated that family with higher income and more members tended to consume more energy. In this study, 189 Dutch households were monitored between October 2002 and March 2003. The importance of socio-demographic variables and psychological variables correlation with residential energy use and energy saving were identified, as in the studies introduced above (Abrahamse & Steg, 2009).

2.5.1.2 Real and Simulated occupant behaviour

The occupants' behaviour has effect on the building energy use, and it leads to significant discrepancy between real and predicted energy performance of buildings (Fabi, et al., 2012). Many studies have identified that discrepancies between real and predicted energy consumption can be affected by the use of the building control systems operated by occupants in different kinds of buildings (Branco, et al., 2004; Marchio & Rabl, 1991; Norford, et al., 1994). Zhun et al developed that the method for identifying and improving behaviour of building occupants in order to evaluate the energy-saving potential of building. The results suggested that occupant behaviour modification lead to achieve the aim of reducing building energy, and that help improve modelling of occupant behaviour in numerical simulation (Zhun (Jerry), et al., 2011). Leth Petersen and Togeby have concluded from their simulation studies that the difference heating systems have effect on the energy efficiency of heating in buildings. It implied that heating systems combustion with oil in buildings have higher energy consumption than that buildings with district heating (Leth-Petersen & Togeby, 2001). As the study from Bishop and Frey, the results indicated that the significant discrepancy between the real occupant behaviour from the behaviour used in the predictions (Bishop & Frey, 1985).

2.5.2 Occupant behaviour influencing on energy consumption in China

The unique history of China, especially the rapid economic development in the last decades, and the population growth, might relate to distinctive occupant behaviour patterns. Moreover, in China, more than 80% of urban families live in apartment buildings (Chen, et al., 2013). It is widely recognized that residential energy consumption is not only influenced by building envelope and insulation level but also influenced by household characteristics, occupant behaviour (Haas, et al., 1998; Olivia Guerra Santin, 2010).

The building characteristics factors likely have effect on energy consumption in China. Other factors such as occupant characteristics and behaviour could thus have a more noticeable impact on energy consumption. As can be seen from some previous researches have attempted to investigate the potential occupant variables have impact on the energy consumption in Chinese residential buildings. A study conducted by Ouyang and Hokao carried out a longitudinal study monitoring occupant behaviour and energy use were recorded once a month in 124 Chinese households from March 2007 to July 2008. The aim of this study is to identify the relationship between energy use and occupant lifestyle, to improve awareness of occupant toward energy efficiency. The occupants are separated into two groups and different behaviours were required. Comparisons analysis results indicated that effective promotion of energy behaviour can reduce household electricity consumption by more than 10%. Additionally, the significant influence of household lifestyle on energy use has also been identified in this study (Ouyang & Hokao, 2009). Cao et al. have shown that individual heating system with control system and old central heating system without control system result in different human thermal sensations can be explained by individual control mode. Therefore, the two types of heating systems have impact on occupant's thermal sensation and behaviours due to different heating set-point. However, this study lack of further analysis about the insulation level and energy consumption (Cao, et al., 2014).

A survey and field observations conducted by Xu et al in China and investigated that the central heating system with TRVs adjusted by occupants in new residential buildings together with new heating payment, it also indicated that momentous difference in the frequency of occupant adjusted the TRVs set-point result in energy saving compared with old traditional heating payment (Xu, et al., 2009). However, in this study, there are not comparisons between old and new residential buildings on further deep research, such as analyses of influence factors (indoor thermal environment, insulation level, thermal sensations, occupants' window behaviours and so on).

2.5.3 Window opening behaviour in buildings

Occupants' behaviour of window opening and heating set-point behaviour of occupants play an important role in determining the energy consumption and indoor environment of a household (Andersen, 2009). It is important to notice that window opening behaviour is not only potential useful for energy saving but also provide an advantageous connect with outdoor conditions (Raijal, et al., 2007). Many previous studies have found significant relationship between window opening behaviour and performance of buildings.

2.5.3.1 Window opening behaviour in residential buildings

Work relating to residential buildings has been reviewed for evidence about which factors affect window operation. Through the previous studies of occupant window opening behaviour in residential dwellings, environmental conditions(indoor and outdoor environment), time of day, type of building, room characteristics have been regarded as the main parameters, which influencing occupant behaviour related to window opening and closing (Dubrul, 1988).

Influence of environmental conditions

Many works have identified that outdoor condition as an important explanatory variable determining on window operation in residential buildings. Johnson and Long monitored occupants' window behaviour in residential buildings between October 2001 to March 2003 and this pilot study was conducted in North Carolina, USA. They observed at least six parameters and found that outdoor temperature, outdoor relative humidity, wind direction and speed significantly impact on operation of windows. However, it was found that there were no correlations between precipitation and window opening behaviour (Johnson & Long, 2005).

In 1977, Brundrett carried out a study of window opening behaviour of families in 123 houses in three seasons. From study, it was found that weather and personal characteristics can be regarded as two important variables influencing the occupant's opening of windows. They reported the strong correlations between outdoor conditions and number of open window in winter and summer times. Additionally, it was found that large sizes of family were more likely open windows than small size of family (Brundrett, 1977).

Fabi et al carried out a study on occupants' window opening behaviour in 15 dwellings from January to August, in 2008, Demark. In the survey the outdoor and indoor environmental parameters were measured. Based on monitored data, the impact of outdoor temperature on occupants opening and closing windows behaviour were identified. Furthermore, correlations between occupants' window behaviour and solar radiation were established in this study (Fabi, et al., 2012a).

In residential buildings, indoor environment also influencing on occupants' window behaviour and previous studies have identified this impact. According to Schweiker et al conducted survey in dwellings in Japan and Switzerland. The measurement of occupants' opening and closing window behaviour was carried out in two dwellings in Switzerland and one student dormitory in Japan. In this study, the correlations between occupants' window behaviour and indoor air temperature were identified (Schweiker, et al., 2012).

Additionally, the statistical analysis carried out from measurement in residential buildings conducted by Antretter et al shown that indoor temperature as a significant variable influencing on window opening behaviour, furthermore, outdoor temperature, outdoor humidity, time of the day and wind speed were regarded as significant variables impacting on window opening by the user in residential buildings (Antretter, et al., 2011).

Fabi et al monitored occupants' window opening and closing behaviour in 15 residential buildings in Denmark, and investigated the correlations between environmental conditions and window opening behaviour. They suggested that the indoor temperature and the indoor CO_2 concentration were regarded as important parameters influencing on the probability of window opening behaviour. It also can found that outdoor temperature is one of the most important proportions of determining the probability of opening and closing a window (Fabi, et al., 2012b).

From study conducted in Japan by Nakaya et al indicated that indoor air temperature is found to be an important influencing factor on occupants' window behaviour in residential buildings (Nakaya, et al., 2008).

Influence of dwelling type

The type of dwelling has effect on the duration time of opening windows and also influence on how wide windows are left open (Fabi, et al., 2012; Dubrul, 1988). A pilot study conducted by Johnson and Long in North Carolina, USA, between October 2001 and March 2003. In this study, the comparison of window opening behaviour in houses and apartments were conducted. It was observed that windows in living rooms and kitchens were open for shorter periods in houses compared with these in apartments. It was also found that the type of the dwelling (detached one-story residence) have impact on the residential openness (Johnson & Long, 2005; Fabi, et al., 2012).

Influence of room characteristics

An extensive study of IEA Annex VIII project (Dubrul, 1988), the state of window opening were measured directly. It is suggested that the type of room have effect on probability of window opening behaviour in dwellings, the most percentages of window opened are in bedrooms. In addition, according to study of IEA Annex VIII project (Dubrul, 1988) found that the orientation of rooms is important as well. From this project, it was observed that when the sunny day, south facing living rooms and bedrooms were more likely to be ventilated for longer periods than similar rooms orientated in other directions.

Erhorn carried out a longitudinal study monitoring occupants' window behaviour in 24 flats in the winter periods of 1st January to 31st December, in 1983, Germany. In the survey, the operations of window and door leaves were recorded by devices. From the results for the different type of room influencing on window opening behaviour, it was found that bedrooms were ventilated more frequently than all type of the rooms on average and the windows opening time in bedrooms exceeded the average for all rooms by some 50% during the entire measuring period (Erhorn, 1988).

In addtion, the behavioural study carried out in 123 British dwellings in 1977 conducted by Brundrett shown that the window in bedroom was mostly opened than other type rooms (Brundrett, 1977). These conclusions were confirmed by other researchers in studies (Antretter, et al., 2011; Fabi, et al., 2012b).

Influence of time of day

From findings of study conducted by Johnson and Long determined the probability of window opening and closing during time of the day. In general, the maximum of window openings occur in the morning. During cooking time of early afternoon, the number of open windows is relatively high (Johnson & Long, 2005).

Erhorn carried out a longitudinal study monitoring occupants' window behaviour in 24 flats during winter season in Germany. In the survey, the operations of window were recorded by device. It was found that the higher probability of window opening during daytime compared with that during nigh time (Erhorn, 1988).

Fabi et al monitored occupants' window opening and closing behaviour in 15 residential buildings in Denmark. It was suggested that the number of windows were most opened during morning time when people wake up (Fabi, et al., 2012b). This conclusion was also identified by other researcher (Antretter, et al., 2011).

Influence of other factors

Many investigations have found that other important factors relate to the window opening behaviour. The window opening behaviour related to aging factors have been investigated by Guerra Santin and Itard. The study conducted in Netherlands in autumn in 2008, it was found that behaviour of elderly people significantly difference from that of younger people. Furthermore, it was also observed that windows in house with children were more opened than those in house without children (Guerra-Santin & Itard, 2010). Meanwhile, results of IEA Annex VIII investigated that the window position was affected by the presence of children. It was also observed that the orientation of window have impact on window operation in residential buildings (Dubrul, 1988). Erhorn have improved little based on the study of Andersen et al and it was observed that the seasonal variations related to the window opening behaviour. It was reflected by results of windows were open longest in summer and shortest in winter (Erhorn, 1988). Andersen et al identified that occupant's gender had a statistical impact on the window opening behaviour (Andersen, et al., 2009).

The studies mentioned above show that environmental conditions (indoor and outdoor), dwelling type, room characteristics and time of day have considerable effect on occupants opening and closing window behaviour in residential buildings. Moreover, each parameter has significant effect on occupants' window behaviour has been confirmed by many previous studies. As a consequence, the influence of different window opening behaviour can potentially lead to different energy consumptions in residential buildings.

2.5.3.2 Predict window behaviour

It is important to understand window opening behaviour effect on prediction of operational energy use in buildings. A model for simulation of office building was applied by Rijal et al, based on this, they use data collected from field surveys to predict the effect of window opening behaviour on energy use. They used logistic regression method when predicting state of window and also they established two window behaviour models that combine both indoor global temperature and outdoor air temperature (Rijal, et al., 2007). Wang and Greenberg reported a study of window operation have effect on indoor environment and building energy consumption. They established simulation model to identify the impact of window operations on building performance for three different types of ventilation systems (Wang & Greenberg, 2015). Nicol reported probability algorithms to predict the state of windows. A statistic approach applied by Nicol was based on some probability algorithms relating occupant behaviour to outdoor temperature. In this study, the window opening behaviour was observed to be correlated with outdoor temperature in three different climates (Nicol, 2001).

2.5.4 Factors influencing occupant heating operation behaviour

Through review of previous studies, there is a definite possibility that the space heating operation have a significant impact on the energy consumption in winter in residential buildings. The occupant interactions with heating controls can be regard as adjustments of heating set-points (using TRVs or Thermostat). Occupants use heating controls in order to offer comfortable indoor conditions which may affect the energy consumption. The factors impacting on occupants' heating behaviour has been summarised by Wei et al, it can be classified as four main factors: occupant related factors, dwelling and system related factors, environmental factors, other factors (Wei, et al., 2014). Different factors that influencing occupants' space-heating behaviour in residential buildings are reviewed in following section 2.5.3.1 to 2.5.3.4.

2.5.4.1 Occupant related factors

Gender: The pervious study of Karjalainen was carried out in Finland, presented that the momentous differences between males and females in thermal comfort, temperature performance and use of thermostats. It was found that male occupants adjust the thermostats more often than female occupants. Additionally, Females were less satisfied with room temperature and prefer higher room temperature than males (Karjalainen, 2007).

Age: Based on previous researchers, age plays an important role on use of heating interacting with energy use. From study conducted in Netherlands by Guerra-Santin and Itard indicated that age is an important proportion of determining energy use, the performance of elderly people in household prefers more hours and higher temperature setting. Furthermore, It seems that the use of heating is unaffected by the children (Guerra-Santin & Itard, 2010). Liao and Chang reported that the elderly residents tend to use more natural gas and oil for space heating than younger residents. The water heating energy consumption decreases as aged becomes older (Liao & Chang, 2002). Age is one of an important determination influencing the demand for space heating (Sardianou, 2008).

Education level: Based on the investigation of Guerra-Santin and Itard showed that the correlations between education level and the use of heating. It has found that the higher the education the person has, the greater the number of hours used with the heating and changed highest set-point on heating pattern (Guerra-Santin & Itard, 2010).

Ownership: A study of survey conducted by Linden et al revealed the occupants who own the houses tend to consume less energy use than occupants who rent houses did (Linden, et al., 2006). Rehdanz have performed the study through use investigation of 12,000 households in Germany in 1998 and 2003. The results revealed that rented-occupied households tend to spend more on heating. However, house-owners consume less energy (Rehdanz, 2007). The findings have been proven by Andersen conducted a study in of Danish dwellings, it was suggested that dwelling ownership conditions affect the use of heating (Andersen, et al., 2009).

Household size: In a study based on the surveys from households in the Greek, Sardinaou investigated the household size have strong correlation with the household energy demand. The results presented that the fuel consumption for heating decreased as consequence of amount of family members increased. In other words, the fewer amount of family members the more energy use for space heating, oppositely, the larger amount of householders, the less energy use for space heating (Sardianou, 2008). Household size having a crucial effect on the space heating has been estimated by Schuler et al used two approaches by simulation models and empirical surveys. The household size is a substantial factor influencing the demand for space heating estimated from data analysis results (Schuler, et al., 2000). However, Guerra-Santin and Itard identified that the household size have no effect on use of space heating (Guerra-Santin & Itard, 2010). Supported by Isaacs et al, it found that there was no relationship between thermostat setting and household size during winter period (Isaacs, et al., 2006).

Family income: Based on study reported by Capper and Scott developed model conducted by Scott (Scott, 1980). There have evidence revealed that household income connected to fuel consumption for space heating in house (Capper & Scott, 1982). Sardinaou have produced a survey of 586 households in Greece. In this study, income was evaluated as significant factor influencing in space heating behaviour and energy use. It revealed that the mean of income increased by 1% lead to the mean of energy consumption increased by 0.04% for space heating (Sardianou, 2008). A substantial correlation between residential energy consumption and income have been demonstrated by Nesbakken in Netherlands, it was found that the higher income in relation with more energy consumption for heating (Nesbakken, 1999). As same approach applied in a discrete-continuous choice model of households in Norway produced Nesbakken. The results indicate that the average income increased by 1% in correlative with average energy consumption increased by 0.06% for space heating (Nesbakken, 2001).

2.5.4.2 Dwelling and heating system related factors

Dwelling type: Santin et al found that the dwelling type has substantial effect on the energy use. The results of statistical analysis determined that more energy used for space heating in individual houses compared to that used in other types of dwellings. In addition, the mean for flats have lowest energy use for space heating compared with other types of dwellings (Santin, et al., 2009). The paper by Sonderegger found that, different house types influencing on the energy consumption from space heating and larger houses have more impact on the consumption than smaller houses (Sonderegger, 1977/78). The correlation between both the type and the age of the building is particularly relevant at choosing utilization of heating has been reported by empirical study of Vaage conducted a survey in Norway, it has been found that households living in the dwellings tend to use electric heating than that living in the apartment (Vaage, 2000). As a model study of households in Norway produced Nesbakken results indicated that the house type have effect on the appliance of heating choice, furthermore, households in detached houses tend to use the heating combination of electricity and wood. It implied that energy demand for heating in apartment or houses are less than those in detached houses (Nesbakken, 2001). Shipworth also suggested that thermostat setting is strongly correlated on dwelling type in UK. The empirical investigation indicated that heating operation were significant difference between detached and mid terrace houses (Shipworth, et al., 2010). A survey of 600 households in Sweden provided by Linden et al described that the households living in detached houses have wider acceptable to lower indoor temperature than that households living in apartments. Additionally, it suggested that the lower indoor temperature interaction with energy use decrease (Linden, et al., 2006).

Dwelling age: Leth-Petersen and Togeby analysed the relationship between policy and energy consumption from 1984 to 1995 in Denmark. They found that the correlations between ages of dwellings and use of energy on heating (Hunt & Gidman, 1982). Conclusion that the lower energy consumption in newer dwellings due to new building regulations (Leth-Petersen & Togeby, 2001). Nesbakken carried out a field study of total energy consumption for Norway, the empirical results exposed that dwelling age have a meaningful effect on energy consumption for space heating, conclusion that higher energy use of space heating in older houses, the reason for this may be due to better insulation in newer houses than in older houses (Nesbakken, 2001). Santin et al conducted a model predicting energy use for space heating in Dutch dwellings. They found that the age of the dwelling have an important effect on predicting energy use of heating, conclusion that newer dwellings use less energy (Santin, et al., 2009).

Dwelling size: Santin et al conducted an investigation for space and water heating in Dutch dwellings. They found that the important correlation between single-family houses and higher temperature, further, household in single-family house tend to use more hours radiators on (Santin, et al., 2009). Dwelling size as a contextual parameter having effect on the space heating has been estimated by Sardinaou in a model study of Greek household (Sardianou, 2008). The results presented that dwelling size have substantial impact on the fuel consumption for heating. Wu et al who analysed the household demand for space heating based on household survey collected from three countries. It was found that households living in houses with more rooms have higher use of energy for space heating (Capper & Scott, 1982; Wu, et al., 2004).

Insulation levels: As a field study conducted by Santin et al in Dutch residential stock and they found that in better insulated house use much lower energy than that in less insulated house. In their investigation, different levels of insulation have significant effect on energy use in different types of dwellings (Santin, et al., 2009). Schuler et al described how insulation standards might be considered as an important determination in demand of space heating for household (Schuler, et al., 2000). The work described in the paper of Haas et al, confirmed that the impact of residential house insulation on the energy demand for space heating (Haas, et al., 1998).

Type of temperature control: The survey of Guerra-Santin and Itard investigated that the type of building temperature control as a factor of determining the heating behaviour. It implied that the occupants living in house using programmable thermostat more often than that manual thermostat. For another study by Guerra-Santin et al, it was found that the presence of thermostat significantly impact on occupant behaviour (Guerra-Santin & Itard, 2010; Santin, et al., 2009). Shipworth et al monitored temperatures in living rooms of English dwellings, and investigated themostat settings reported by participants, together with building, technical and behavioural data. They suggested that the mean temperature setting in dwellings with a thermostat is slightly lower than that in dwellings without a thermostat. It also can found that households with a programmable thermostat use heating system more often than households with manual thermostats (Shipworth, et al., 2010). Nevius and Pigg performed a study of 299 households equipped with thermostats in Wisconsin in 1999. The result of regression analysis indicated that energy use for space-heating marginally in correlation to dwellings operated with programmable thermostats. Furthermore it was found that thermostat-setting behaviour has an indirect effect on heating energy consumption (Nevius & Pigg, 2000). A survey and field observations conducted by Xu et al (Xu, et al., 2009) in China and investigated that the heating system with thermostatic radiator valves(TRVs) adjusted by occupants. The results indicated that momentous difference in the frequency of occupant adjusted the TRVs set-point depended on the results of different habits among occupants.

Type of heating system: Through the literature there are several studies have focused on the types of HVAC system present in the domestic dwelling have effect on the use of heating systems. A survey of occupant behaviour was carried out by Andersen et al in Danish dwellings. They suggested that the great correlation between type of heating system and energy consumption of heating in dwellings. It also found that the heating combination with wood burning influence strongly on the control of heating (Andersen, et al., 2009). The findings supported by Guerra Santin and Itard have developed a questionnaire in Dutch households and found that the type of heating system and ventilation system have impact on the occupants' behaviour (Guerra-Santin & Itard, 2010).

2.5.4.3 Outdoor conditions

A survey of occupant behaviour was carried out by Andersen et al in Danish dwellings. It found that the use of thermostatic radiator valves set-point space heating have strong correlations with outdoor temperature (i.e. outdoor relative humidity and the wind speed) (Andersen, et al., 2009). As study of Knudsen mentioned that the heating behaviour of domestic dwellings was related to the outdoor temperature. The heating behaviour influenced by factors of the outdoor temperature, wind speed, solar radiation and outdoor relative humidity (Larsen, et al., 2010).

2.5.4.4 Other factors

Energy price: Scott estimated that a 1% increase in price, fuel consumption for space heating decrease by about 0.4% (Scott, 1980). The correlation between energy consumption for space heating and energy price has been confirmed by empirical study of Vaage conducted a survey in Norway to investigate the role of energy price impact on energy demand directly (Vaage, 2000). Nesbakken focus on Norwegian household energy demand for space heating, It has shown that increase in the average price of energy used in the chosen heating technology is estimated to reduce energy consumption (Nesbakken, 2001).

The above review provides guidance on influencing factors for identify in this project heating occupants' behaviour in residential buildings. It can be used in further comparison analysis of occupants' heating behaviour related to the energy-saving potential in newer residential building.

2.6 Thermal comfort

Thermal comfort has a significant impact on occupants' productivity and health, and it plays an important role when evaluating the performance of buildings. Thermal comfort has been defined as "*that condition of mind which expresses satisfaction with the thermal environment*" (Fanger, 1970).

2.6.1 Concept of thermal comfort

2.6.1.1 Thermal comfort variables

Fanger stated that the factors influence the condition of thermal comfort can be divided into two main parts: four environmental factors and two personal factors (Fanger, 1970).

Environmental factors:

1. Air temperature
2. Mean radiant temperature
3. Relative humidity
4. Air velocity

Personal factors:

1. Clothing insulation

2. Metabolic heat production (activity level)

It is important to take account to the other personal physiological factors, such as age, gender, body proportion, menstruation cycle, food and draught. However, according to Fanger these personal physiological factors do not define thermal comfort significant (Sugini, 2016). Thermal comfort can be achieved by many different combinations of above variations and the details of these are described following.

Air temperature is defined as "*the temperature of the air surrounding occupant*" (ASHRAE55, 2004), and which is most important environmental variable, measured by dry bulb temperature.

Mean radiant temperature (MRT) defined as "*the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure"* (ASHRAE55, 2004). In addition, MRT calculated many ways, which is a dominant element in the thermal comfort equation (Robert Bean, 2013). However, mean radiant temperature cannot be measured directly and it can be approximated by globe temperature (t_g) measurements by using a 150 mm diameter globe thermometer. A value for mean radiant temperature can be calculated by $t_{g,}$ air temperature and air velocity for the environment using the following equation 1 (British Standard, 2001):

$$\bar{t}_\tau = \left[\left(t_g + 273\right)^4 + \frac{0.25\times10^8}{\varepsilon_g}\left(\frac{|t_g - t_a|}{D}\right)^{1/4} \times \left(t_g - t_a\right)\right]^{1/4} - 273 \qquad \textbf{(1)}$$

Where

tτ = Mean radiant temperature (°C)

t_a = Air temperature (°C)

t_g = Globe temperature (°C)

ε_g = Emissivity of the globe (-)

D = Diameter of the globe (mm)

Relative humidity is a measure of the amount of water vapour in the air related to the maximum amount that it can contained at a given temperature (British Standard, 2001).

Air velocity can be determined by air movement around the body, and which is a quantity defined by its magnitude and direction. Air velocity can be considered as determining heat transfer by convection and evaporation at the position of a person (British Standard, 2001).

Clothing is an important factor influencing the occupants’ thermal sensation. It is named clo, which is played a role on insulating cover between the human body and surrounding environment. In experimental survey, using garment clo values in ISO 7730 the subjects.

Metabolic heat production (activity level) is one of important personal factor include the metabolic rate. It is maybe affected by food and drink, as well as the state of acclimatization (Auliciems & Szokolay, 2007). An appropriate metabolic rate was assumed for the subjects can use table given in ISO 7730.

Operative temperature (OT) is a measure that combines the air temperature and the mean radiant temperature into a single value to express their joint effect. Nicol et al states the definition of OT as *“It is a weighted average of two, the weighted depending on the heat transfer coefficients by convection (h_c) and by radiation (h_r) at the clothed surface of occupant”*. Operative temperature cannot strictly be measured directly but in practice it is not very different from air temperature. It defined by using the following equation 2 (Nicol, et al., 2012):

$$\boldsymbol{t_o = \frac{(h_c * t_a) + (h_r * t_r)}{h_c + h_r}} \qquad \textbf{(2)}$$

Where

t_o = Operative temperature, °C

t_a = Air temperature, °C

t_r = Mean radiant temperature, °C

h_r = Heat transfer coefficient by radiation, W/ (m^2•K)

h_c = Heat transfer coefficient by convection, W/ (m^2•K)

2.6.1.2 Thermal comfort standards

To determine appropriate thermal conditions, a number of national organizations whose standards have international influence make a significant contribution to creation knowledge of thermal comfort. The international standards concerned with thermal comfort (i.e. ASHRAE and ISO standards) are mostly based on theoretical analyses of human heat exchange performed in mid-latitude climatic regions in North America and northern Europe (Olesen & Parsons, 2002; Djongyang, et al., 2010; ISO7730, 2006). The most important thermal comfort standard is ISO 7730, which is based on Fanger's Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) index (Fanger, 1970).

2.6.1.3 PMV model

In the past 40 years, the Predicted Mean Vote (PMV) model developed by Fanger has been considered as the most important landmark, and it has been adopted by many building design standards, such as ASHRAE 55 and ISO 7730 to evaluate thermal comfort conditions in buildings. PMV is base of theoretical of comfort equation developed by Fanger and which is relation with four environmental factors and two personal factors (Fanger, 1970). In addition, Fanger indicated the equation gives information on how to combine the variables in order to provide optimal thermal comfort (Sugini, 2016). It was therefore possible to predict level of thermal comfort by using six variables. Fanger's heat balance equation that described as follow:

$$\boldsymbol{H - Ed - E_{sw} - E_{res} - L = K = R + C} \quad \textbf{(3)}$$

Where

H = the internal heat production;

Ed = the heat loss by water vapour diffusion through the skin;

E_{sw} = the heat loss by evaporation of sweat from the surface of the skin;

E_{res} = the latent respiration heat loss;

L = the dry respiration heat loss;

K = the heat transfer from the skin to the outer surface of the clothed body;

R = the heat transfer by radiation from clothing surface;

C = heat transfer by convection from clothing surface

Fanger’s model is based on combination of heat balance and physiology of thermoregulation in order to determine a range of comfort temperatures (Djongyang, et al., 2010). Commonly use seven point Psycho-physical scale as a measure for the thermal sensation (ISO7730, 2006):

$+3$	*Hot*
$+2$	*Warm*
$+1$	*Slightly Warm*
0	*Neutral*
-1	*Slightly Cool*
-2	*Cool*
-3	*Cold*

However, PMV equation is too complex and it is hard to calculate manually, it is therefore possible to use computer software to calculate the value of PMV (Fanger, 1970).

2.6.1.4 Adaptive model

Thermal adaptation essentially dynamic and which can be divided into three modes of adaptation: behavioural adjustment, physiological acclimatization and psychological habituation or expectation (Brager & de Dear, 1998). In detailed, behavioural adjustment contains three parts: 1) Personal adjustments (i.e. adjust clothing or activity and eat or drink hot/cold food etc.); 2) Physiological adjustment (i.e. open/close windows, adjust HVAC controls etc.); 3) Cultural adjustments (i.e. scheduling activities, siestas and so on). Psychological acclimatization can be separated to two parts: 1) Genetic adaptation; 2) Acclimatization. Psychological habituation or expectation is thermal perceptions depended on occupants' past experiences and expectations of indoor climate (de Dear, et al., 1997).

Work relating to adaptive model has been reviewed in studies, as study conducted by Hoof and Hense optioned that adaptive model have effect on energy use in air conditioning building during summertime, furthermore, it could lead to 10% decrease in energy consumption (Hoof & Hensen, 2007). From review conducted by Halawa and Hoof indicated those adaptive model applications in naturally ventilated building reflect better thermal sensation of occupants than those PMV model applications (Halawa & Hoof, 2012). Nicol and Humphrey developed adaptive approach and they mentioned that the adaptive behaviour correlation to outdoor temperature in naturally ventilated building.

2.6.2 Thermal comfort in buildings

2.6.2.1 Field studies of thermal comfort in buildings

People spend majority of the time occupancy in buildings. Therefore it is essential to evaluate the thermal sensation of occupants in buildings and understanding how people have feeling to their thermal environment and useful to ensure the thermal comfort responses to efficient energy use in future work.

Works have been carried out in office are reviewed. Koranteng monitored temperature and relative humidity in 15 office buildings in Ghana. It was found that uncomfortable indoor environmental conditions caused by high relative humidity values (Koranteng, 2011). In Malaysia, Tail et al carried out thermal comfort study in a 21 storey high-rise office building, aiming to assessing thermal comfort and users' perception of landscape garden. In the survey, four environmental parameters were measured concurrently by proper sensors and occupants' thermal sensation and use of garden and landscape preference were evaluated by questionnaires survey. The results show that the significant differences in four thermal parameters in three different types of gardens (Taib, et al., 2010). Simons et al also carried out a study of assessing thermal comfort in multi-story office building in Ghana. In this survey, 195 participants were recruited and asked to report their thermal sensation by using questionnaires. During the survey period, four environmental parameters and outdoor climatic data were monitored by instruments. They found that PMV model predicts thermal comfort in mechanical ventilated buildings better than that in naturally ventilated buildings (Simons, et al., 2014). Following the above study performed by de Dear and Fountain carried out a replication of ASHRAE sponsored San Francisco filed study (RP- 462). The study was undertaken in 12 air conditioned office building in Australia, there were 836 participants were asked to provide their thermal sensation and clothes insulation levels were assumed. It found that the guideline in ASHRAE 55 and ISO 7730 maybe not suitable for hot and humid climatic zone. They also reported that there are slightly difference of thermal sensation between male and female (de Dear & Fountain, 1994). In Germany, Kuchen and Fisch carried out an analysis of thermal comfort in 25 office buildings during winter season. During the survey, the environmental parameters were measured by proper instruments and simultaneous questionnaires were collected from office users. Results show that high correlation between PMV model and AMV model (Kuchen & Fisch, 2009).

Numerous studies in both thermal environment and thermal responses have been investigated in residential buildings as well (Han, et al., 2009; Wang, 2006; Cao, et al., 2014; Luo, et al., 2014; Hong, et al., 2009; Oseland, 1994). Hong et al. focused on thermal comfort of occupants on domestic conditions in England in winter, results showed that better insulation and energy efficient heating system lead to better thermal comfort and related to energy demand (Hong, et al., 2009). Becker and Paciuk used the Fanger’s model as standard and conducted field study in 189 dwellings in winter, the results from survey showed the actual mean votes(AMV) were significantly higher predicted mean votes(PMV) and gender, age of occupants have no obviously effect on thermal responses (Becker & Paciuk, 2009). In the study carried out in Libya, Ealiwa et al undertook survey of thermal comfort in 27 new air-conditioned and 24 old naturally ventilated residential buildings during summer seasons in 1997 and 1998. In the survey, 237 residents were asked to report their thermal sensation. From the survey it was found that the measurement of PMV model can be use in new dwellings to predict the occupants of actual thermal sensations (AMV) according to ISO 7730. Furthermore, occupants in old dwellings provide more satisfied and thermal neutral than that in new air-conditioned buildings. Dick and Thomas (1951) reported that 70% of the observed variance of open vents and casements could be accounted for by the outdoor air temperature, based on field measurements carried out in 15 houses during 26 winter weeks. Additionally, they suggested that another 10% of the observed variance was contributed by the wind speed. In their study, the wind speed and direction, the inside and outside air temperatures were measured and recorded automatically using particular devices, and the state of windows was recorded manually. Moreover, previous researchers report about thermal comfort on winter conditions related to energy consumption in residential buildings. Seligman et al conducted survey in 500 homes at Twin Rivers in the eastern USA and they observed that homeowners' summer electricity consumption could be predicted by comfort and health concerns (Seligman, et al., 1977/78). It also found that the greater the importance of personal comfort and 'health' to the household, the higher the consumption for air-conditioning.

2.6.2.2 Thermal comfort studies in Chinese residential buildings

Through the reviews, limited numbers of thermal comfort studies have been conducted in residential buildings in China. Field study of Cao et al. in Chinese residential buildings showed that the mean indoor temperature individual boiler heating system compared to that in district heating system exceeded 1.6°C (Cao, et al., 2014). Field study of the thermal comfort conditions in residential buildings were conducted in two zone of China, Yang et al. found that 68% of occupants feel slightly cool in winter and neutral temperature were much higher than indoor air temperature (Yang, et al., 2013). Cao et al. have shown that new individual heating system and old central heating system result in different human thermal sensations can be explained by individual control mode. Therefore, the two types of heating systems have impact on occupant's thermal sensation due to different heating set-point and they found that the dwellings operated by new individual boiler heating system have more acceptable for thermal environments. However, there has not been any further analysed about the insulation level and energy consumption (Cao, et al., 2014). As a consequence, the investigation of thermal comfort in old and new residential buildings is need to be developed, especially focus on different building standards employ with different heating and bill systems.

2.7 Summary

This chapter has provided a thorough review of current scene on energy consumption in buildings and especially in residential sector. In section 2.2 reviewing energy consumption of building sector in the world and also the current status of the Chinese residential building sector. Section 2.3 present currently available legislation and code on buildings in China, furthermore reviewed current status of energy conservation for residential building. Through section 2.4, a review has been worked out on the existing heating system and reform of heating payment in Chinese residential buildings. In section 2.5, occupant behaviour is one of important factor impact on energy consumption, furthermore, occupant behaviour related to heating energy consumption and an attention is also given on potential factors that influence on occupant window behaviour and heating behaviour. Concept of thermal comfort and thermal comfort in building related to energy consumption were described in section 2.6.1 to 2.6.2. The main aim was to explore the effect of recent Chinese government policy on heating behaviour and energy consumption in Chinese residential buildings. From review, previous studies focus on energy consumption in residential buildings in China. The findings of literature review show that the few researchers focus on this area. There are three main factors related to energy consumption can be discussed, insulation level, occupant behaviour and thermal comfort. The typical samples of residential building stock in China were reviewed. The potential factors impact on occupant behaviour in window operation and heating usage were reviewed. Related to this, the influences of new heating and control system on window operation and heating behaviour in previous studies have not been estimated. The each potential factor will be explored by using new and old case study residential buildings. It is necessary to compare measured data from old and new apartments stocks. Moreover the measured data will be use to validate a simulated model.

Chapter 3

METHODOLOGY

3 Methodology

3.1 Introduction

This chapter introduces the experimental methods and simulation methods that were applied in this study to achieve aim and objectives. Two typical multi-stories residential building were chosen as case study buildings. Experimental methods provide an investigation of the data collection, measures, equipment and site monitoring. The indoor thermal environments, window operation, heating energy consumption and thermal comfort in both new and old case study buildings were investigated. Questionnaire methods were used to assess the thermal sensation of occupants and to identify the occupant heating behaviour. In addition, simulation methods describe the detailed procedures that were selected to validate the thermal modelling.

3.2 Design of Case studies and research method

3.2.1 Overview

The chapter of literature review explore how potential factors impact on energy consumption in other studies and confounding factors need to be considered in the analysis. Thus the appropriate longitudinal measurements were designed in this chapter. An early introduction of the residential building sector in China was presented in section 2.2.3. Recalling the findings, the majority of existing common residential buildings are multi stories buildings. In numbers, heating account for 59%, and it is most of residential building energy use. There are huge amount of new residential buildings have been built within past 10 years in China, it account for around 60% of all residential buildings. There are also about 35% residential buildings are aged between 10-30 years. Therefore, selected case buildings for investigation can to be suitable as typical type of residential building.

The study concentres on typical new and old residential buildings that has multi-stores, seven new apartments and seven old apartments in different floors in each building, and a mix of female and male occupants. Each apartment has one living room, two bedrooms, one kitchen and one bathroom. The indoor and outdoor thermal environment will be monitored continually and each household characteristic were carried out by using questionnaires survey and energy consumption will be compared as well. Moreover, the field study of thermal comfort was designed in two buildings. The impact of the new design standard has been evaluated in relation to a number of aspects, that include building construction, indoor thermal environment, occupant behaviour, thermal comfort and building energy consumption. Therefore, the study focus on comparing energy simulation and thermal performance results based on different building design standards. Before monitoring of thermal environments, a risk assessment of measuring was completed. Additionally all experimental devices had been tested carefully by electricity technicians in the Laboratory. Figure 3.1 describes a timeline of exactly when all measurements and data collection occurred during whole investigation period.

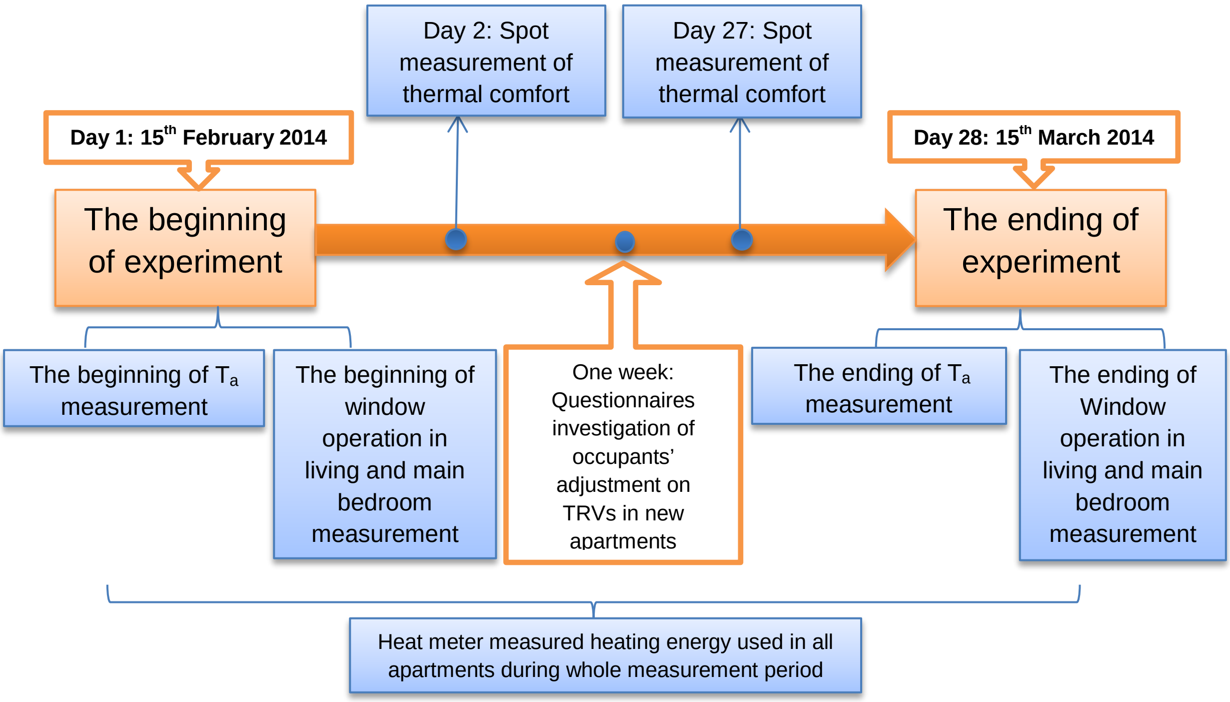


Figure 3.1 The timeline of overview on-site measurement

3.2.2 *Concept of occupant behaviour models*

The window state was monitored every one minute by a pair of window contactors and the change of window states (either from open to close, or from close to open) was instantly recorded by appropriate devices. As mentioned in experimental data collection section 3.3, it was recorded in binary form (i.e. open is 1; closed is 0). As mentioned in reviews of window opening behaviour in residential buildings (section 2.5.3). Previous studies has been reviewed for evidence about which factors affect window operation, there are environmental conditions (indoor and outdoor environment), time of day, type of building, room characteristics). When analysing the window opening data, it could be treated as a stochastic process. Furthermore, time of day, type of building, room characteristics will be analysed in further section. Logistic regression models were used to predict the state of windows and it was established by Nicol at the beginning (Nicol, 2001). Logistic regression model was used to prediction of probability of state of windows with respect to the indoor/outdoor air temperature as explanatory variables. It was reported by Nicol and Humphreys. They established two window behaviour models that combine both indoor global temperature and outdoor air temperature (Nicol & Humphreys, 2004). Nicol collected data about window open or closed and presented probability algorithms relate to occupant behaviour and outdoor temperature. Probit analysis assumes that the probability of an event happening increase as the stimulus increases. Probit analysis was used in his study and results conclude that the probability of window is opened increases relating to outdoor temperature increases. Logit model defined the probability p of an event having happened and this method used in his study (Nicol, 2001):

$$\log\left(\frac{p}{1-p}\right) = a + bx \tag{4}$$

Where a is constants, b is constants, x is a variables.

Rijal et al developed a window prediction approach and the relationship is relies on logit relationship, the equation 5 and 6 as follow (Rijal, et al., 2007):

$$\log(p) = \log\left(\frac{p}{1-p}\right) = bT + c \tag{5}$$

Whence

$$\boldsymbol{p} = \frac{\boldsymbol{e}^{(\boldsymbol{bT}+\boldsymbol{c})}}{\boldsymbol{1}+\boldsymbol{e}^{(\boldsymbol{bT}+\boldsymbol{c})}} \tag{6}$$

Where

p is the probability that the window is open

T is the outdoor or indoor temperature

b is the regression coefficient for T

c is the constant in the regression equation

Logistic regression models are used to model the probability of specific event happening (i.e. state of window opening or closing, state of dwelling control). In logistic regression analysis, the study of Andersen reported the effects of the explanatory variables as odds ratio and the definition of odds is the probability of window opening separated by the probability of window closing (Andersen, 2009).

3.2.3 Building description

The investigated buildings are located in the City of Xi'an, Xi'an city is located at latitude 34°16´N, longitude 108°56´E, is typical city in cold zone in the northwest of China, and belongs to the Shaanxi province. The two types of buildings are both multi-stories residential buildings. The new residential building (as shown in Figure 3. 2a) was built in the past 5 years and the old building (as shown in Figure 3.2b) was built late 1990s.

Table 3.1 lists information of investigated households for both old and new buildings. Seven households in new building and seven households in old building were selected to investigation during heating period. The areas of old apartments are between 76.3m^2 to 98.3m^2, overall 671.3m^2 and the locations of floors are between second floors to fifth floors. Additional, the areas of new apartments are between 79.5m^2 to 104.2m^2, overall 581.7m^2 and the locations of floors are between second floors to six floors.

Figure 3.2(a) the typical investigested new building; (b) the typical investigated old building

Table 3.1 Individual information of new and old apartments

	No	**Floor Areas**	**Number of occupants**	**Ownership**	**The location of floors**
New apartment	1	79.5 m^2	2	owner-occupied	Third floor
	2	104.2 m^2	2	owner-occupied	Sixth floor
	3	83.3 m^2	2	owner-occupied	Third floor
	4	83.3 m^2	2	owner-occupied	Fifth floor
	5	104.2 m^2	2	owner-occupied	Fifth floor
	6	83.3 m^2	2	renter-occupied	Fourth floor
	7	79.5 m^2	2	owner-occupied	Second floor
Old apartment	1	76.3 m^2	2	owner-occupied	Second floor
	2	76.3 m^2	2	owner-occupied	Fourth floor
	3	84.8 m^2	2	owner-occupied	Fourth floor
	4	84.8 m^2	2	owner-occupied	Fifth floor
	5	76.3 m^2	2	owner-occupied	Third floor
	6	84.8 m^2	2	owner-occupied	Second floor
	7	98.3 m^2	2	owner-occupied	Fifth floor

The new residential building operated by district heating system with TRVs in each radiator, the room temperature can be adjusted within a range based on the requirement of the building occupants. The typical radiators of hydraulic heating system in new apartment can be seen in Figure 3.3(a).

The old residential building supplied by district heating is equipped by water flow through with constant speed via pipe network. Each old apartment is heated by a district heating system with constant water flow. The changes of water temperature are operated by heat source or substation, in accordance with the changes in outdoor temperatures and have no direct control for occupants and thus they can only open the window or door to adjust their thermal environment. The Figure 3.3(b) presented the selected radiators of hydraulic heating system of old apartment for investigation. No hot water system is installed in both new and old apartments.


(a) (b)

Figure 3.3 (a) district heating system with TRVs in typical new apartment; (b) district heating system without TRVs in typical old apartment

3.2.4 Comparison of building envelope conditions

The two monitored buildings have different types of walls. The old building was built with solid brick walls with a thickness of 240mm, and the metered new buildings built with cavity filled with air walls with a thickness of 240mm. Table 3.2 lists important definitions of building construction for both old and new buildings, information of investigated households.

Table 3.2 General information of constructions and materials of old and new building

	External wall	**Window**	**Roof/Ceiling**			
	Material of envelops			*High of floor*	*Apartment layout*	*Built year*
New building	240mm cavity bricks, EPS insulation, plastering mortar inside and outside	Double-glazing	Concrete, Roof Bricks, Chalk	2.8m	One living room, two bedrooms	Late 2010s
Old building	240mm solid bricks, plastering mortar inside and outside	Single-glazing	Concrete, Roof Bricks, Asphalt	2.8m	One living room, two bedrooms	Late 1990s

3.3 Experimental data collection methods

3.3.1 Indoor environmental measurement

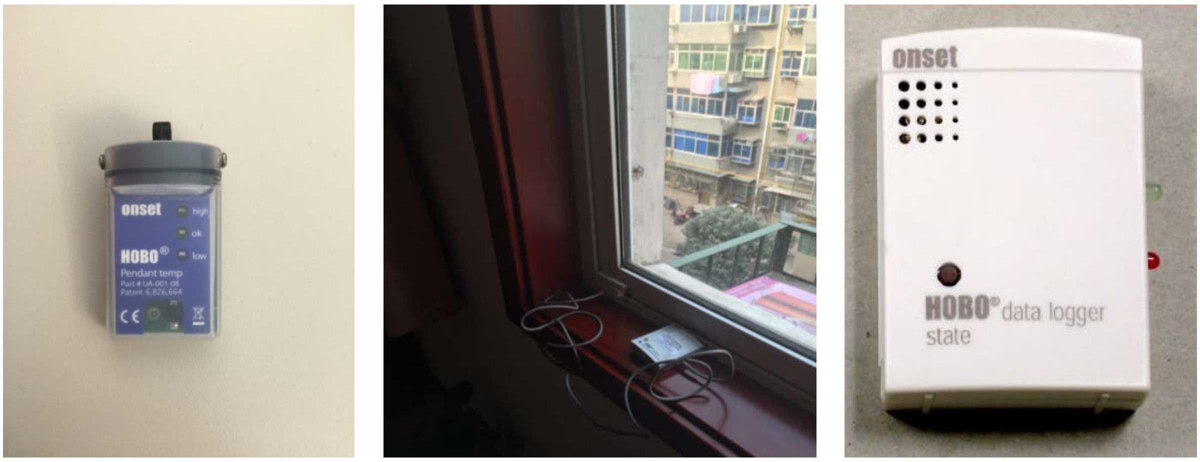
In the study, seven apartments from each building were monitored longitudinally between 15 February and 14 March, 2014. Table 3.3 gives the location and information of measurement devices during investigation period. Figure 3.4 illustrates the measurement devices and the detailed technical specifications are listed in table 3.4.

Table 3.3 The location and information of measurement sensors

Sensors	Location of sensor	The Height of sensor	Duration times
Air temperature sensor	Living room and main bedroom	1.0m	Interval of ten minutes
Window state sensor	Living room and main bedroom	1.0m on the windowsill	Interval of one minutes

The indoor air temperature of each apartment was measured and recorded at an interval of 10 minutes by a Hobo data Logger Hobo UA-001 temperature sensor (Fig 3.4a), in both living room and main bedroom. Based on the BSRIA guideline, internal temperature sensors at a height of 1.0m above floor were considered to be adequate level of sensor positions (BSRIA, 1998a). Therefore the temperature sensors placed in the middle of living room and bedroom in each apartment, the height is around 1.0

m. Furthermore, in order to ensure the realistic accurate result of measurements, the sensors location was positioned away from local heat sources, direct sunshine, window, and door. Outdoor temperature was also monitored with HOBO data logger at an internal of 10 minutes during whole measurement period. Detailed specification of this device is presented in table 3.4. The window operation sensors were placed at window in living room and main bedroom in each apartment. The window state was monitored every one minute by a pair of window contactors and the change of window states (either from open to close, or from close to open) was instantly recorded by HOBO U9-001 loggers (‘1’ for open; ‘0’ for closed) it shown in Figure 3.4c.



(a) Indoor Air Temperature; (b) Window operation monitoring; (c) Hobo data logger of window state;

Figure 3.4 Measurement devices

Table 3.4 Specifications of measurement devices

	HOBO Pendant Loggers (UA-001-08)	**HOBO State Data Logger (U9-001)**
Measurement Range	–20°C to +70°C	External contact input: Passive relay switch or contact closure - minimum duration 1 second
Measurement Accuracy	±0.53°C from 0 to 50°C	N/A
Response time	10 minutes	N/A
Time accuracy	±1 minute per month at 25°C	

3.3.2 Energy consumption

The new apartments are heated by central heating system with TRVs on each radiator and heat meters. The heating energy consumption was measured by in-situ measurement of the recording by the residential heat meter in each apartment. The typical heat meter in new apartment was presented in Figure 3.5a. The old apartments are heated by central heating system without any control and heat meters. Therefore, the heating energy used in each apartment in old building must be measured manually. The hydraulic flow rate for the heating pipes in each apartment was spot measured by a Portaflow 330 flow meter, the flow measurement accuracy from ±0.5% to ±2% of flow reading for flow rate >0.2m/s, given in Figure 3.5b (Micronics, 2014). Additionally, the water temperature of supply and return heating pipes in each apartment logged for one hour interval. Based on the measured flow rate and flow water temperatures, the heat consumed by each apartment can be calculated. The methods of calculated energy consumption were based on the theory of heat meter in new apartments. The principle of heat measurement for the theory of heat meter can be described as follow approach. The approach can be described using the following equation (Ye, et al., 2005):

$$\boldsymbol{Q = \int_{V0}^{V1} k\, \Delta T dV} \qquad \textbf{(7)}$$

Where

Q is the quantity of the heat (W),

V is the volume of the liquid passed through the flow sensor (kg/s),

k is the heat coefficient of the heat-conveying liquid at specific temperature and pressure W/(m^2°C),

ΔT is the temperature difference of the heat-conveying liquid at the flow and return terminal (°C).

Equation (7) is apply to water as the heat conveying liquid, with the flow temperature between 50-95°C and the return flow temperature between 5-94°C, respectively. Thus, the calculation of energy use in heating system in old apartments can be seen from equation 8, as following:

$$Q = C_p \times m \times (T_{in-p} - T_{out-p}) \tag{8}$$

Where

Q	Quantity of the heat (W)
m	Mass flow rate of water in pipes (Kilograms)
T_{in-p}	Temperature from input pipe (°C)
T_{out-p}	Temperature of output pipe (°C)
C_p	Specific heat of water (approximate 4.2J/kg °C)

(a) **(b)**

Figure 3.5 (a) Typical heat meter installed on input water pipe of heating system in new residential buildings; (b) Site monitoring of water flow rate of heating by Portaflow 330 instrument

(Micronics, 2014)

3.3.3 Thermal comfort of on-site measurements and instruments

The field study of thermal comfort in each apartment was carried out in-site measurements. It can be divided into two main parts: objective experimental measurements and subjective questionnaires survey. During the whole experimental investigation periods and site surveys from each apartment were collected by observer at the beginning day of whole experimental periods and also collected at the end day. The clothes insulation and thermal sensation were carried out from the interviewed survey and the simultaneous measurement of environmental parameters of air temperature, mean radiant temperature (MRT), air velocity and relative humidity.

The subjective surveys were based on the thermal sensation reported by occupants. In addition, the gender should be considered into the evaluation of thermal comfort in all apartments. Gender differences on thermal comfort were investigated in Chinese building during winter period by Lan et al. It was found that females prefer warmer conditions than males (Lan, et al., 2008). As a consequence, equilibrium between males and females has also been considered during the selection of occupants. In this study, there are two occupants that will participate in each apartment that one male and one female. Moreover, the ages of occupants range from 18 to 65. Detailed of subjective occupants in each apartment are presented in further section 3.4.3 and details of subjective survey are described in section 3.4.4.

A HOBO data logger was used to measure the indoor air temperature in living room and main bedroom in each apartment. For measuring the relative humidity (Figure 3.6a), the range is from 5% to 95% RH. Furthermore, mean radiant temperature was estimated from globe temperature measured by using about 38mm black ball global temperature thermometer. This method has been confirmed by other researchers (Humphreys, 1977). The indoor global temperature was measured by HOBO TMC1-MD temperature sensor with a 38mm diameter black table-tennis ball and measured by HOBO U12 data loggers (Figure 3.6b) In order to make sure the measurement accuracy, the 38mm black table-tennis ball thermometer had been calibrated in chamber. Indoor air velocities were measured by hot-wire anemometer (Figure 3.6c) at 0.1m, 0.6m and 1.1m height during interview survey. The range of the hot-wire anemometer for air velocity is from 0 to 15m/s with an accuracy of ±0.05 the equipment accuracies correspond to ISO7726 (ISO 7726, 2001). In addition, detailed specifications of experimental devices are presented in table 3.5.

Table 3.5 Specifications of experimental instruments

	HOBO Temp/RH/Light External Data Logger (U12-012)		**Hot-wire anemometer**
	RH	*Temperature*	
Measurement Range	5% to 95% RH	-20°C to 70°C	0-15 meters per second
Measurement Accuracy	±2.5% from 10 to 90% RH	±0.35°C from 0 to 50°C	0.05
Response time	1 minute, typical to 90%	6 minutes, typical to 90%	5 second
Time accuracy	1 minute per month at 25°C		

(a)RH; (b) Global Temperature measurement; (c) Air velocity;

Figure 3.6 Experimental devices in thermal comfort studies

3.4 Occupants' interview survey

3.4.1 Questionnaires of occupants' window behaviour

For measuring the occupants' window behaviour, window opening /closing were measured in every one minutes in all old and new apartments. The further questionnaires of reasons for opening windows were conducted in each apartment. In questionnaires(see in Appendix A), the suitable reasons were investigated, the personal reasons of opening windows is three scales of yes or no, following with question: "The window were opened to ventilate because, too hot, air smelled bad for fresh air, remove moisture due to condensation on windows ?". In section 4.3, further evidence to support the reasons for window opened will be discussed.

3.4.2 Occupants' adjust TRVs in new apartments

According to the new standard of heat metering and controlling system for central heating system, the design of indoor temperature for TRVs is $18°C \leq T_{max} \leq 25°C$ and $5°C \leq T_{min} \leq 12°C$ (MOC, 2009). In this study, the questionnaires (see in Appendix B) were conducted to 7 households in the new residential buildings with TRVs and heat metering devices. In order to assess occupants' heating behaviour in the new apartments, a further questionnaire was distributed to each household (living and main bedroom), asking them to self-record their heating behaviour (i.e. adjustment of the TRV settings) over a whole week period. The occupants were asked for filling out the self-questionnaires, as for instance, when they turn off/turn on the TRVs need to mark in questionnaire. The detailed of questionnaire is given in Appendix B. Moreover, when they adjust the TRVs of radiators need to write down the range of scale values of TRVs on questionnaire. Therefore, according to the questionnaires, the occupants' behaviours in TRVs regulation can be identified. It could be related to the fluctuation of indoor air temperature and variation of flow rate for heating. In next section further evidence to support the relations between them will be discussed.

3.4.3 Subjective survey of thermal comfort

The thermal sensation of occupants was investigated by observer using questionnaires. There have 14 household in total for two types group of buildings, the each occupant of investigated worked in same city. The questionnaire was developed based on the standard of ISO 10551 (ISO 10551, 2001) and used in each apartments. In order to make sure the participants can clearly understand each question and to ensure valid and accurate results, before the survey the questionnaire was translated into Chinese (Liu & Qin, 2006). A consent form (see in Appendix B) was issued and the actual mean votes (AMV) form was explained to them. There are three main questionnaires: first is application form to take part in the thermal experiments that questions about the participants' age, physical conditions, the culture background, education level, income level and normal lifestyle of each participant. Second is the main thermal sensation of participants and how they feel about the thermal environments. It includes the 7-point ASHRAE sensation scale, ranging from -3(cold) to +3(hot) and 0(neutral). Each scale were explained and translated to Chinese. Additionally, the three thermal performance scales were provided by warmer, no change, cooler. And the personal acceptability of indoor thermal environment is two scales of yes or no, following with question: “Would you accept this indoor thermal environment?”. The third one is used to identify the clothing insulation values for females and males and it divided into two parts, one is participants identifying the clothing insulation values and given a total figure for it, another one is observed by observer from distance. The details of questionnaires can be seen in Appendix B.

The subjective measurement was aimed to collect their thermal sensation in their living space. In the study, each apartment had one male and one female participant, aged between 22 and 57 years. Before the survey, the details of the experiment were described to all participants. Meanwhile, a consent form was issued and how to fill out the thermal sensation questionnaire administrated to real participant was explained. During the survey, the occupants were asked to sit in the living room, and then were asked to report their thermal sensation at the end of the survey. Meanwhile, air temperature, mean radiant temperature, air speed and relative humidity were measured according to the ISO standard (ISO 7726, 2001). In this study the insulation of the chair is assumed to be 0.35clo as all participants were sitting on a fabric sofa during the survey (McCullough, et al., 1994).

The spot measurement of thermal comfort survey was conducted on individual occupants who were seated watching TV in living room in each apartment. All occupants were kept seated for 45mins and they were asked to fill AMV form after 30mins and 45mins. The survey involved 28 subjects in total, 14 females and 14 males. Averagely, there were two times questionnaires survey were conducted during interviews, one was presented at begin day of whole experiment periods, and another one was presented at the final day of whole experiment periods. Therefore, valid questionnaires are 112 in total and there were 56 questionnaires from new apartments, and 56 questionnaires from old apartments, respectively.

3.4.4 Household information in new and old apartments

A background survey were also conducted in both new and old apartments, the questionnaires collected information about occupant themselves. Two occupants in each apartments were found in the survey; females (14), males (14). Table 3.6 describe that the number of apartments and individual social background in each apartments. The household size of each apartment includes two people in this study. From the table, the employments of each household are presented. The individual occupant income and education level are given as well. The age of oldest occupant in new building is 53 and the youngest one is 22. In contrast, the age of oldest occupant in old building is 57 and the youngest one is 26. The most of household are buying their apartments in both new and old building. A mentioned before in Table 3.1 lists information of investigated households. Only one household in new building is rented apartment. The most common apartments located in floors are between two to six floors that are in the middle of buildings.

Table 3.6 Individual background in new and old apartments

	No	**Age of occupants**		**Income range(RMB/per Year)**	**Education level**	
		Woman	Man		Woman	Man
New Apartments	1	38	39	60,000 -- 70,000	College Degree	College Degree
	2	45	46	100,000 --150,000	College Degree	Bachelor
	3	26	26	60,000 -- 70,000	Bachelor	Bachelor
	4	25	28	60,000 -- 80,000	College Degree	Bachelor
	5	51	53	200,000 -- 300,000	High School	High School
	6	27	27	50,000 -- 70,000	Master	Bachelor
	7	22	23	30,000 -- 40,000	College Degree	Bachelor
Old Apartments	1	55	57	50,000 -- 70,000	College Degree	College Degree
	2	53	56	60,000 -- 80,000	Bachelor	College
	3	52	54	80,000 -- 100,000	Bachelor	College
	4	26	27	60,000 -- 80,010	College Degree	Bachelor
	5	35	38	Up to 300,000	Bachelor	Master
	6	33	37	60,000 -- 80,000	Bachelor	Bachelor
	7	28	28	50,000 -- 70,000	Bachelor	Bachelor

3.5 Model simulation method

3.5.1 Overall simulated methods

In consideration of the new building standard and new heating systems applied in residential buildings in China, the actual energy consumption of new and old building can be validated by using thermal modelling methods. The field measured data and all parameters of building performance are application to EnergyPlus by using interface Designbuilder. This method have been recommended by Mohammad et al for validating the measurement data and computational fluid dynamics results, they confirmed that DesignBuilder can predict simulated results with good accuracy (Mohammad , et al., 2013). The structure of case study building was modelled based on the actual structure and detailed information. Individual apartments were simulated by using individual modelling blocks. The weather file of hourly outdoor temperature, and relative humidity values generated with real actual measured by data logger that was input into simulation models. The construct of building, doors and windows are input into each models based on actual size and structure of all apartments. In order to evaluate the experimental validation and make sure good accuracy simulation results. The orientation of rooms and type of windows were considered into all simulation models.

3.5.2 Input parameters for building model

3.5.2.1 Simulation model development

The actual structure of case study buildings drawings were imported to simulation tool. In model designed, the new and old buildings were divided into each new and old apartment model blocks. The sample of model block is shown in Figure 3.7a and sample of simulated 3-D case study building in simulation tool is shown in Figure 3.7b.

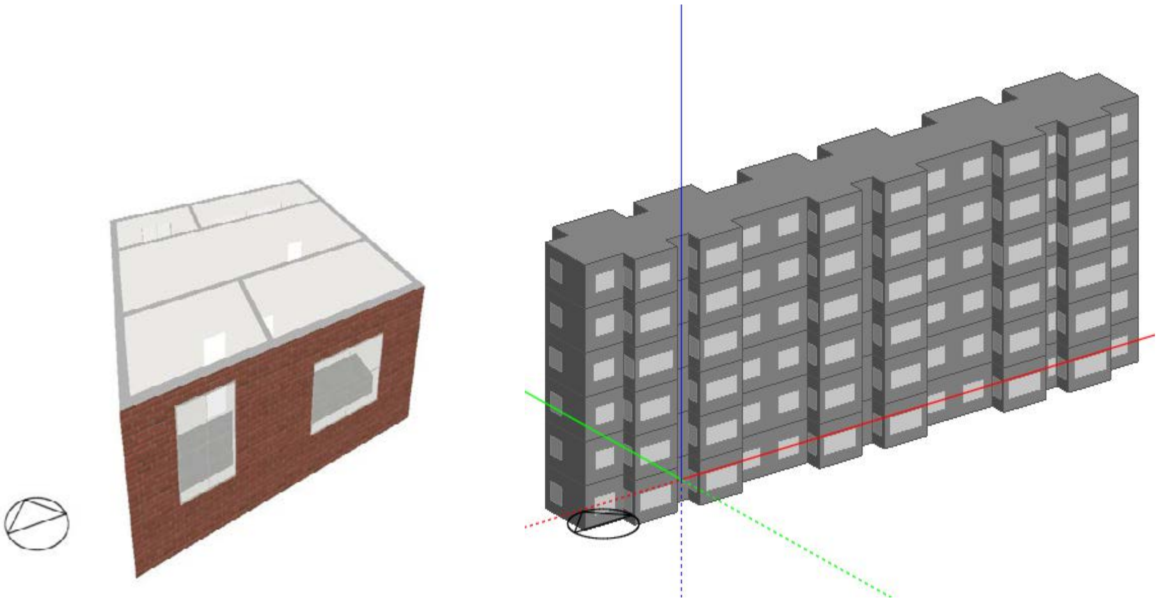


Figure 3.7 (a)Sample of Model Block; (b) The case study building 3D view of design model

The sample of layout of imported floor plan is given in Figure 3.8. It contains five different zones: One Living room, two bedrooms, one kitchen and one toilet. As stated above, the building construction and envelops based on design standards for new and old building, heating set-point, window operation are acquired from real measured data, and they are applied in model block. Further detailed of information will be introduced in next section.

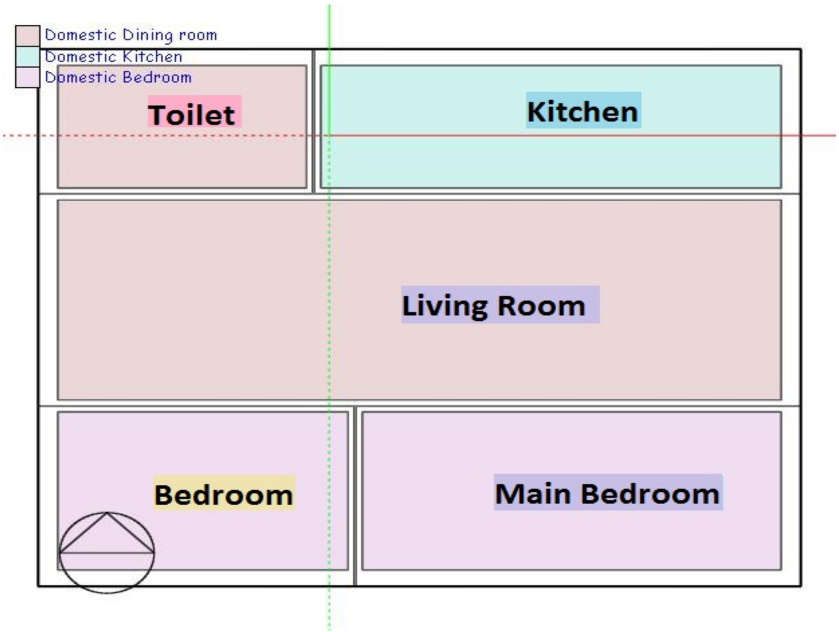


Figure 3.8 layout of floor plan

3.5.2.2 Envelop and constructions

In order to determine the thermal transmittances (U-value) of new and old apartments, the construction material properties were given from actual construction specifications for apartments. The details of procedure for working out U-value are given in Appendix E. Table 3.7 summaries that the insulation level as input for both old and new model blocks, based on the building design standards (JGJ26-2010, 2010; GB50176-93, 1993). It shows that the new model block offers much better insulation than the old one. In old apartments, single glazing were used for windows and in new apartments, double glazing were used for windows.

Table 3.7 Thermal transmittances (U-value) of old and new model blocks

	Old Model Block(W/m2°C)	New Model Block(W/m2°C)
External Wall	1.69	0.7
Window	5.8	3.6
Floor	2.48	2.28
Roof	2.48	2.28

The construction design requirement of R-value and insulation materials of both new and old models were comply with Chinese standards shown in table 3.8 and table 3.9. Therefore the real detailed information about new and old apartment construction and insulation levels used as input in both old and new model blocks.

Table 3.8 Construction design and U-value of external wall for old and new model blocks

	Construct Materials	**Thickness (mm)**	**Thermal Conductivity (W/m °C)**	**R-value**
Old Model Blocks	Brick	240	0.65	0.37
	Plastering mortar	20	0.5	0.04
	R_{si}	N/A	N/A	0.123
	R_{se}	N/A	N/A	0.06
	∑R	N/A	N/A	0.59
	U-value		1.69	
New Model Blocks	Brick	240	0.65	0.37
	Air	15	0.024	0.625
	EPS	10	0.046	0.21
	Plastering mortar	10	0.47	0.002
	R_{si}	N/A	N/A	0.123
	R_{se}	N/A	N/A	0.06
	∑R	N/A	N/A	1.40
	U-value		0.7	

U-value of Roof for old and new model blocks. It is seen that the construction materials of the roof consist of two kinds of material, concrete and roof brick, and concrete covers 80% of the total area. The windows used in old apartments is single glazing with a U-value of 6.0W/m^2°C and that in new apartments is 3.6W/m^2°C.

Table 3.9 Construction design and U-value of roof for old and new model blocks

	Construct Materials	Thickness (mm)	Thermal Conductivity (W/m °C)	R-value
Old Model Blocks	Concrete	75	0.4	0.19
	Asphalt	20	0.75	0.02
	Plastering mortar	20	0.5	0.004
	R_{si}	N/A	N/A	0.123
	R_{se}	N/A	N/A	0.06
	$\sum R$	N/A	N/A	0.4
	U-value		2.48	
New Model Blocks	Concrete	75	0.4	0.19
	Plastering mortar	20	0.5	0.004
	Polyester	20	0.05	0.04
	Asphalt	20	0.75	0.027
	R_{si}	N/A	N/A	0.123
	R_{se}	N/A	N/A	0.06
	$\sum R$	N/A	N/A	0.44
	U-value		2.28	

3.5.2.3 Weather data

In this study, before the simulation, the hourly weather data and Relative Humidity have been monitored by appropriate data logger. Hourly Relative Humidity and hourly solar radiation of whole experimental periods are given in Figure D-01(in Appendix D) and Figure 3.11 respectively and it input into simulation model. New case study building and old case study building are located in same city, different districts. To make sure the outdoor air temperature have no significant different between two regions, the T_{out} around new building and old building were measured separately. Figure 3.9 depicts the linear regression correlations between T_{out} around new building and T_{out} around old building, R value is 0.998, which means there is no significant difference of outdoor air temperature between two regions. Therefore, in this study, in order to achieve accurate value of the outdoor temperatures were chosen by mean of two location measurements. Figure 3.10 depicts measured hourly mean outdoor temperature of whole experimental periods and it applied to simulation model.

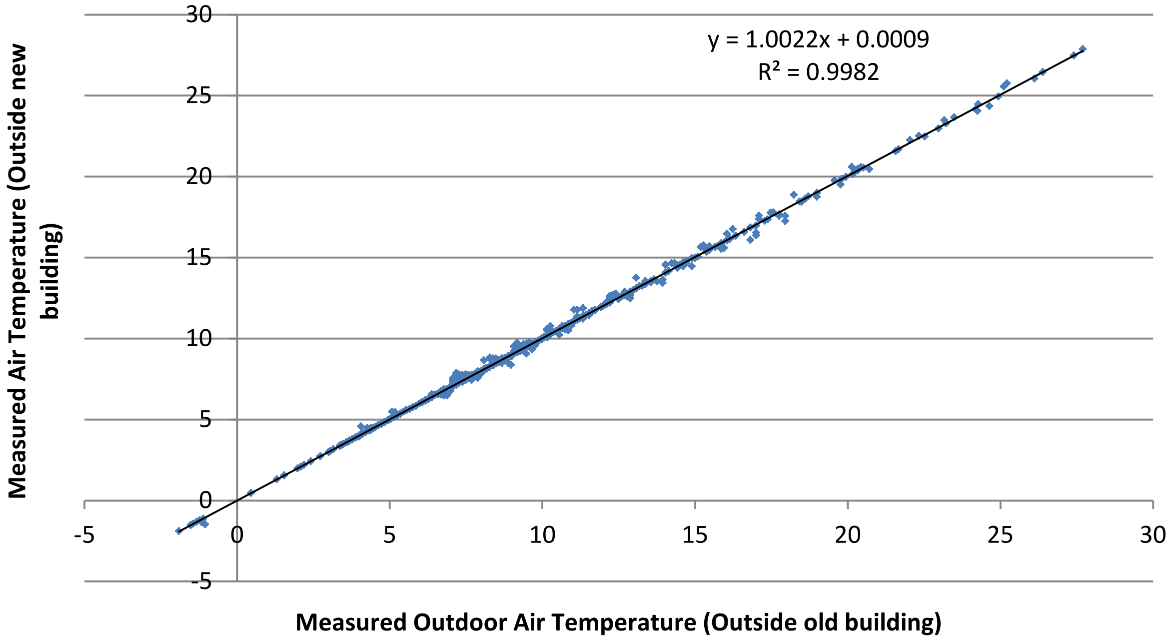


Figure 3.9 Correlation between measured outdoor air temperatures around old building and measured outdoor air temperatures around new building

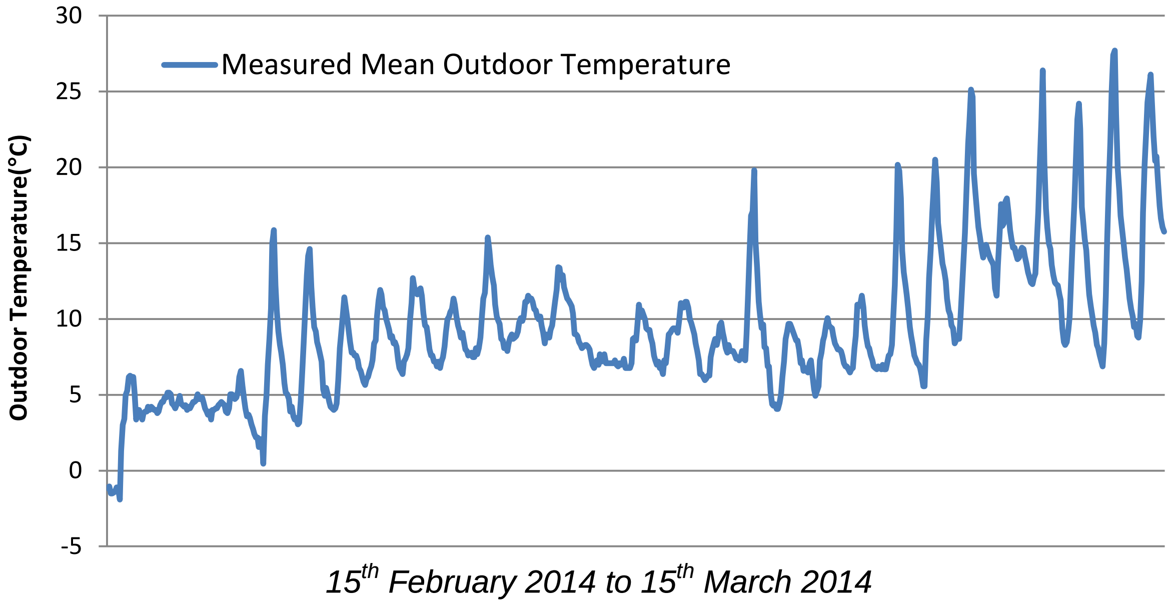


Figure 3.10 Hourly mean outdoor temperature plot for period 15th February 2014 to 15th March 2014

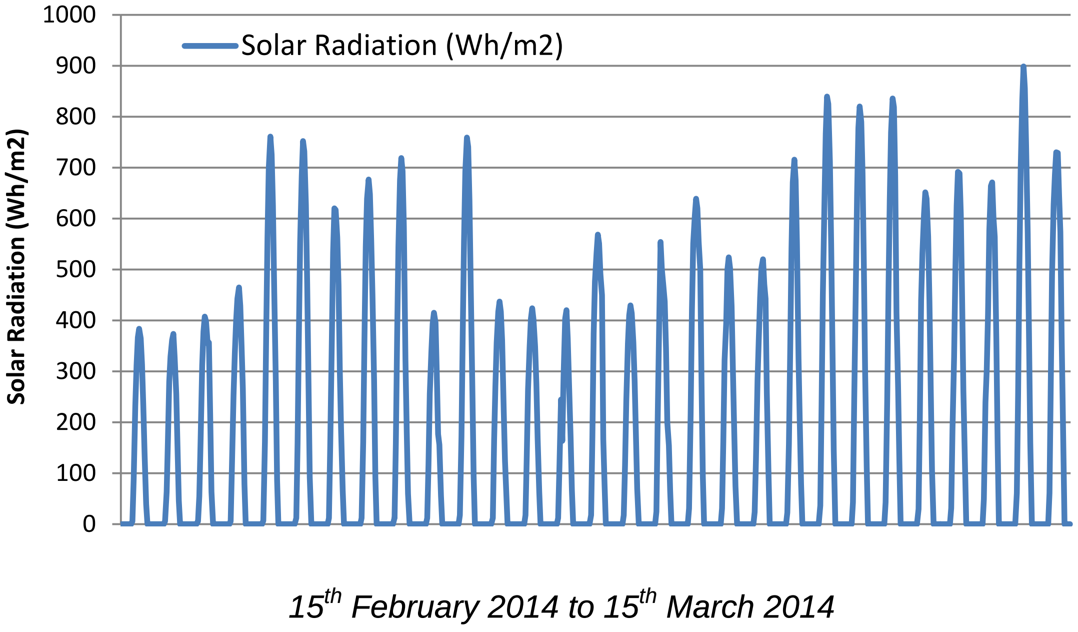
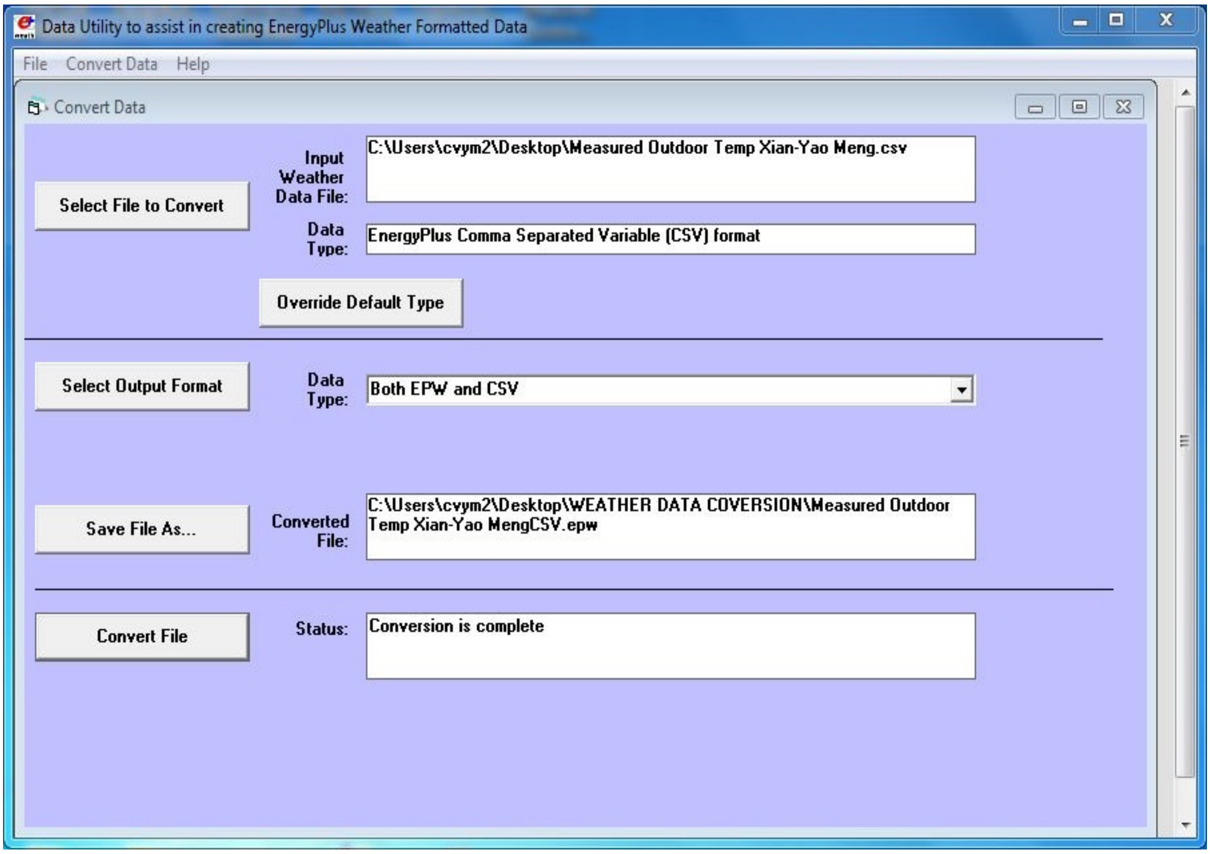


Figure 3.11 Hourly Solar Radiation plot for period 15th February 2014 to 15th March 2014

Figure 3.11 depicts measured hourly solar radiation of whole experimental periods and it applied to simulation model. In order to run actual measured outdoor temperature data in EnergyPlus, the file of actual EPW are required, therefore, the progress are given in Figure 3.12 and further procedure is given in Figure 3.13 following. Figure 3.12 presents the detailed of original file of outdoor temperature convert to appropriate EPW file into simulation models. Figure 3.13 describes the actual measured date were chosen to apply in model data before simulation.



Input Weather Data File: C:\Users\cvym2\Desktop\Measured Outdoor Temp Xian-Yao Meng.csv

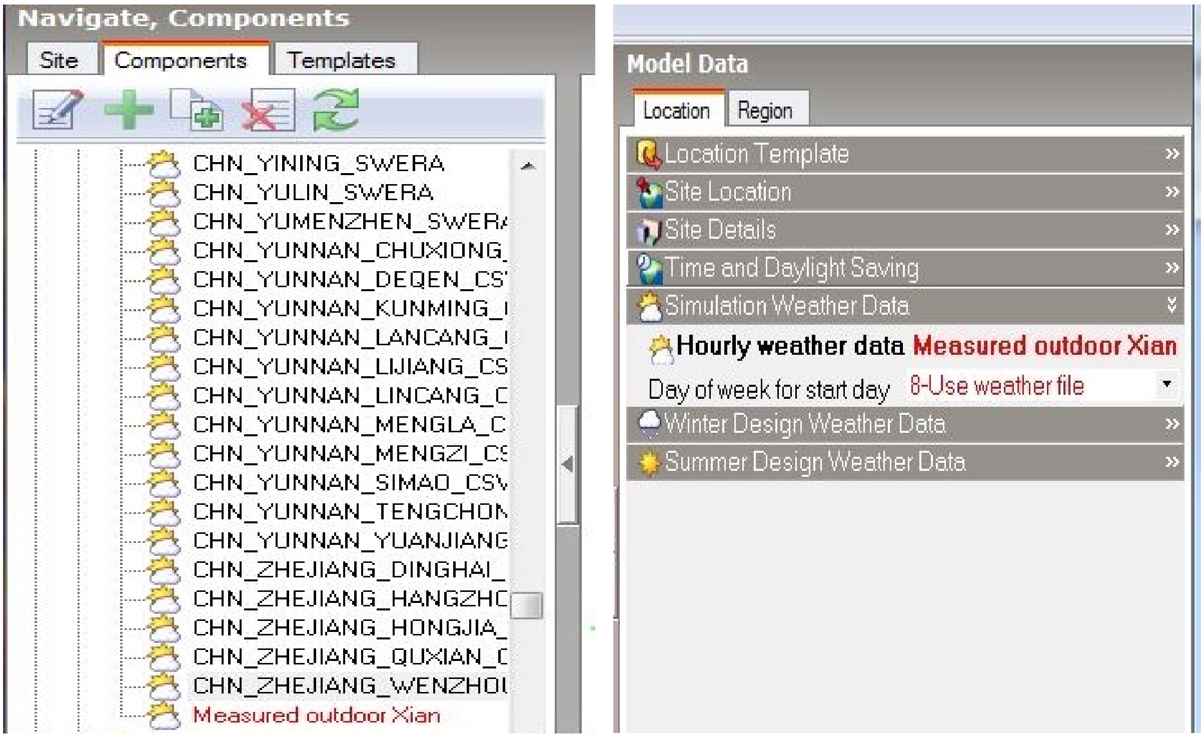
Data Type: EnergyPlus Comma Separated Variable (CSV) format

Data Type: Both EPW and CSV

Converted File: C:\Users\cvym2\Desktop\WEATHER DATA COVERSION\Measured Outdoor Temp Xian-Yao MengCSV.epw

Status: Conversion is complete

Figure 3.12 Procedure of convert an EPW file



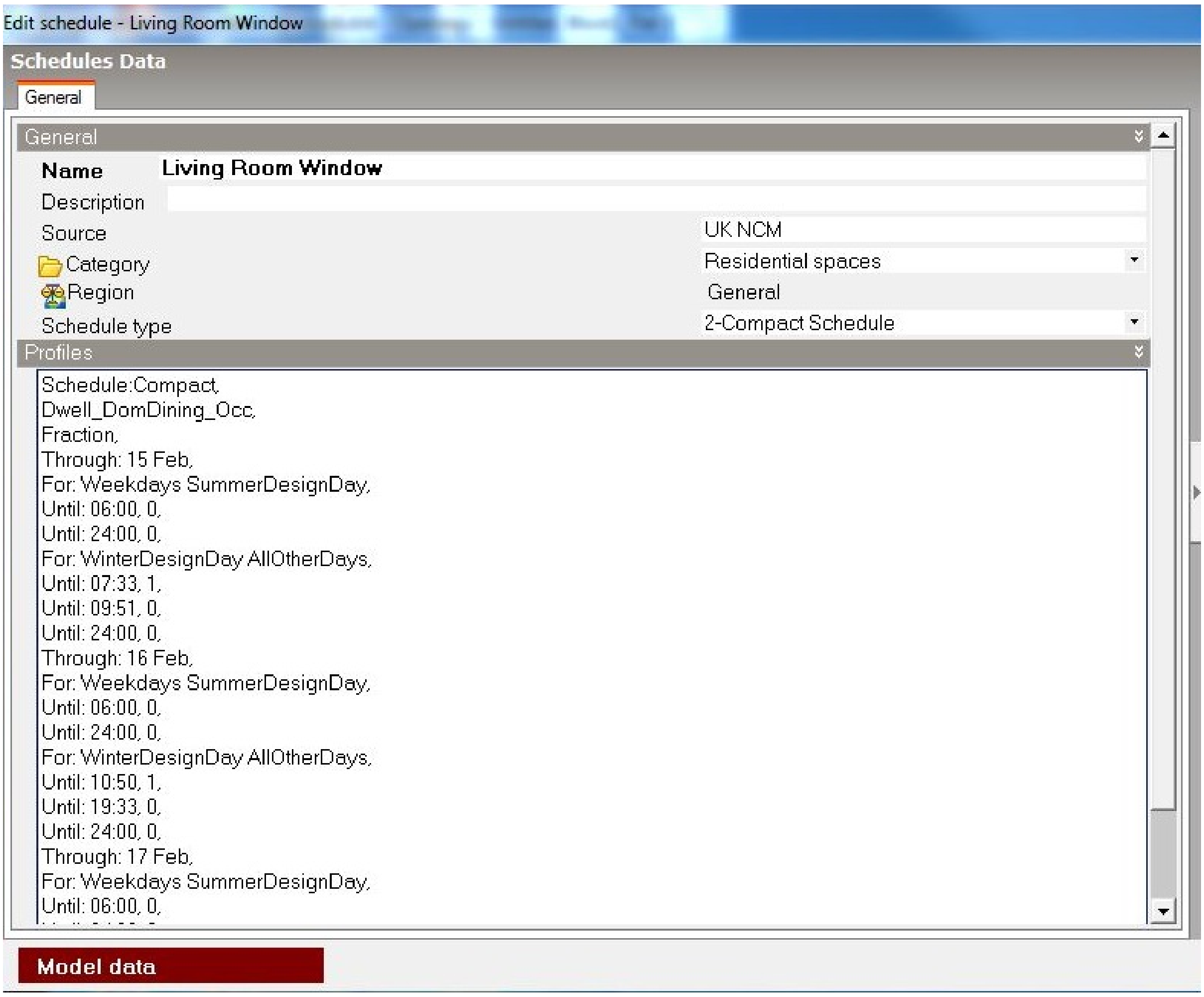
Hourly weather data Measured outdoor Xian

Day of week for start day 8-Use weather file

Figure 3.13 Procedure input file of weather data set up in simulation model

3.5.2.4 Window state and occupants activities

Modelling occupant window behaviour, the state of window opening is defined as a binary, 1 for open and 0 for closed. It is good for using statistical method that is logistic regression. The detailed information about monitoring window state in all apartments is provided in section 3.3. To achieve the most accurate analysis, the window behaviour simulation is based on monitored data of window opening/closing. Figure 3.14 depicts a sample of how the window opening/closing schedule input into simulation model. It gives a sample of window opening/closing time in living room based on actual measured data of whole experimental period. The air change rate is assumed as 0.6ac/h, according to building standard were considered into simulation.



Name Living Room Window
Description
Source UK NCM
Category Residential spaces
Region General
Schedule type 2-Compact Schedule

```
Schedule:Compact,
Dwell_DomDining_Occ,
Fraction,
Through: 15 Feb,
For: Weekdays SummerDesignDay,
Until: 06:00, 0,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 07:33, 1,
Until: 09:51, 0,
Until: 24:00, 0,
Through: 16 Feb,
For: Weekdays SummerDesignDay,
Until: 06:00, 0,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 10:50, 1,
Until: 19:33, 0,
Until: 24:00, 0,
Through: 17 Feb,
For: Weekdays SummerDesignDay,
Until: 06:00, 0,
```

Figure 3.14 Sample input of window opening/closing schedule in living room based on actual measured data

For occupant daily presence, the input of activity schedule was based in questionnaire survey from field study and it was designed on an hourly basis. There are two occupants per each apartments, typical occupancy pattern are listed in table 3.10.

Table 3.10 Input of typical occupancy pattern into simulation models

	Occupancy Hours	
Room	**Weekdays**	**Weekends**
Living room	5:00pm - 11:00pm	08:00am - 11:00pm
Bedroom	8:00pm - 07:00am	08:00pm - 11:00pm
Kitchen	7:00-9:00am & 17:00-19:00pm	7:00-9:00am & 17:00-19:00pm

3.5.2.5 HVAC system and other parameters input to simulation model

The simulation input of heating set-point temperatures based on measured mean indoor temperature in both new and old building. Based on design standard (JG/T-195, 2007), the room temperature set-point of Thermostatic radiator valves(TRVs) indicate that the maximum opening temperature value is $18°C \leq T_{max} \leq 25°C$ while the minimum opening value is $5°C \leq T_{min} \leq 12°C$. Therefore, for the heating operated with control system in each apartment of new building, the heating set-point in model blocks use the mean experimental indoor temperature. Table 3.11 show that the setting of heating set-point temperatures in living room and main bedroom in model block. However, set-point temperature of the kitchen and bathroom are normalized by Chinese building standards (GB 50093, 2003).

Table 3.11 Mean indoor temperature input in both old and new model blocks

	Mean Indoor Temperature(°C)	
Room	**Old model block**	**New model block**
Living room	22.5	20.7
Bedroom	21.5	19.6
Bathroom	18	18
Kitchen	15	15

For HVAC zone data model, the collected experimental data is inserted. “Hot water radiator heating, nat vent” were inserted in appropriate HVAC template. In addition, hot water system was not supplied in model. In another set of simulation, natural ventilation was turned on, and time of window operation inputs were replaced with schedule of real monitored window states. The default inputs of occupant densities and occupancy schedules from the DesignBuilder database replace with the investigated occupant densities and occupancy schedules. It was given in section 3.5.2.4. And the computers, office equipment were turned off. Furthermore, the most appropriate DesignBuilder template was chosen in each zone (i.e. for the main bedroom zone, the DesignBuilder “Domestic bed room: an area primarily used for sleep” was used).

3.5.3 Four simulation scenarios

The study focus on evaluating different building design standards have effect on the thermal and energy performance of buildings, through a comparison of various potential main parameters (insulation level and construction, heating set-point, occupant window behaviour) of two types of residential buildings. Compare with old case study building comply with old building standard. For the new case study building comply with new building standard, the change of the construction (insulation level) had been improved, heating system operated with individual control system and new heat reform payment system had been changed. Measured data of each parameter were used for calibrating the simulation model. The influence of new building standard on energy consumption should be examined by simulation. Therefore to predict and identify how each parameters effect on energy consumption, old case study building applied with new standard in simulation procedure. To predict the energy saving potential of each parameter on the heating energy consumption, the energy consumption was simulated with EnergyPlus. Four simulation scenarios were studied:

1) Scenario 1

Old apartment model block applied with input of U-value and construction according to old building standard. Therefore U-value and construction materials of new apartments was set up into old apartment model block, no changes have been made to HVAC system, window operation schedule and other input parameters.

2) Scenario 2

Old apartment model block applied with input of heating set-point according to measured indoor climates in old apartments. The simulation input of heating set-point temperatures based on measured mean indoor temperature in new apartments. Therefore it was set up into old apartment model block. No changes have been made to U-value and construction materials, window operation schedule and other input parameters.

3) Scenario 3

Old apartment model block applied with input of window operation according to measured data in old apartments. Therefore window operation schedule measured in new apartments was set up into old apartment model block, no changes have been made to HVAC system, U-value and construction materials and other input parameters.

4) Scenario 4

Old apartment model block combine all three interventions: window operation, heating set-point and insulation level.

The four scenarios were simulated for old model block through the 15th February to 15th March 2014 period. The comparison of each scenario of energy saving have been worked out in further results chapter five.

3.5.4 Heat loss assessment

3.5.4.1 Fabric heat loss

Heat loss can occur through the building envelop, and according to second law of the thermodynamics, heat from warm areas flows out through the fabric of buildings to cold areas. Theoretical losses include transmission losses and ventilation losses. Heat loss is estimated in steady state conditions and it is obvious to state that steady state condition is an idealized situation when indoor and outdoor temperatures are constant (Bishop, 2008). Heat is lost from a dwelling can be divided into two ways.

Fabric heat loss is caused by heat through all floors, walls, roofs, windows and doors. And then all elements added together to give total fabric heat loss all.

Basic heat loss through any given surface can be calculated using the following equation:

$$\boldsymbol{Q_f = U \times A \times (T_{in} - T_{out})} \quad \textbf{(9)}$$

Where Q_f = Fabric heat loss, Watts

U = Thermal transmittance (U-value) of building elements, W/m^2 °C

A = Area of surface of building, m^2

T_{in} = Internal temperature of building, °C

T_{out} = external temperature of building, °C

Then, overall heat loss through fabric of the any building can be calculated using following equation:

$$Q_{f\text{-total}} = \sum\left[U \times A \times (T_{in} - T_{out})_{walls} + U \times A \times (T_{in} - T_{out})_{windows} + U \times A \times (T_{in} - T_{out})_{roofs} + U \times A \times (T_{in} - T_{out})_{floors} + U \times A \times (T_{in} - T_{out})_{doors}\right]$$

3.5.4.2 Ventilation heat loss

Ventilation heat loss can be calculated from the volume of the residential buildings and an assumed value for the number of air change per hour (ac/h). In Chinese residential buildings, the standard offer a value of 0.6 ach of air change rate value. When window closed, the air exchange between internal and external is achieved by crevices called infiltration in buildings. Furthermore, windows openings lead to uncontrolled air changes in buildings (CIBSE, 1999).

Basic heat loss through any given surface can be calculated using the following equation:

$$\mathbf{Q_v = 0.33N \times V \times} (\boldsymbol{T_{in} - T_{out}}) \quad \textbf{(10)}$$

Where Q_v = Ventilation heat loss, Watts

N = Number of fresh air change per hour of the building, ac/h

V = Volume of the inside space of the building, m^3

T_{in} = Internal temperature of building, °C

T_{out} = external temperature of building, °C

Thus,

Total building heat loss is then can be described using following equation:

$$\mathbf{Q_{total} = Q_f + Q_v} \tag{11}$$

In practices, the ventilation losses due to infiltration can be omitted because it is hard to estimate the air entering the building through the ventilation openings (Koene, 2011). The window openings can often be controlled by occupants and then impact on air exchange rate in buildings (Marr, et al., 2012). CIBSE guide gives air infiltration rates for various buildings and the maximum average air change rate are given in table 3.12 (CIBSE, 1999). Johnson carried out a study in houses and measured air exchange rate with windows. From study it was suggested that geometric mean to change from 0.76h-1 for no openings to 1.51 h-1 for one opening, 2.30 h- 1 for two openings and 2.75h-1 for three or more openings (JOHNSON, et al., 2004). Therefore, the air change values can be corrected under reasonable conditions in practice range from 0.60-2.30 ac/h.

Table 3.12 Maximum average air infiltration rates in air changes per hour

	'Leaky' building (ac/h)	Moderately 'tight' building (ac/h)
Dwellings - 1 story	1.15	0.40
Dwellings - 2 stories	1.00	0.35
Apartments - 1 to 5 stories	1.00	0.50
Apartments - 6 to 10 stories	1.60	0.55

In order to calculate the areas of each element of new and old apartments, the details of dimensions for the area calculation can be seen from table 3.13. The thermal transmittance (U-value) of new and old apartments was given in Table 3.7. Temperature difference between indoor and outdoor can be determined by using measured data. The details of procedure for working out sum of calculated areas in each apartment are given in Appendix C. It can be seen from above description, total fabric and ventilation loss can be worked out by using equation 9, 10 and 11.

Table 3.13 Dimensions for area calculations

Apartment Type	Dimensions for total areas (m^2)	Total volume of inside space of apartment (m^3)	Apartment Type	Dimensions for total areas (m^2)	Total volume of inside space of apartment (m^3)
Old apartment 1	140.92	78.120	New apartment 1	160.50	95.564
Old apartment 2	140.92	78.120	New apartment 2	165.76	98.784
Old apartment 3	165.88	98.952	New apartment 3	162.68	96.824
Old apartment 4	165.88	98.952	New apartment 4	162.68	96.824
Old apartment 5	140.92	78.120	New apartment 5	165.76	98.784
Old apartment 6	165.88	98.952	New apartment 6	162.68	96.824
Old apartment 7	190.52	120.904	New apartment 7	160.50	95.564

3.6 Summary

This chapter introduce the experimental methods and simulation methods that were applied in this study, in order to achieve aim and objectives of research project. In the study, seven apartments from old and seven apartments from new building were monitored longitudinally between 15 February and 14 March, 2014. The experimental methods are used to monitor the thermal environment, occupant behaviour and energy consumption and each household characteristic were carried out by using questionnaires survey, and this is to provide input parameters set for analysing and discussion related to the dynamic thermal modelling methods. In addition, simulation methods describe the detailed procedures that were selected to validate the thermal modelling. Thereafter, the field study of thermal comfort was designed in two buildings.

Chapter 4

OCCUPIED APARTMENTS: MEASUREMENT, RESULTS AND DISSCUSSION

4 Apartments measurement, results and discussion

4.1 Introduction

This chapter describes the results of measurements made in both new and old apartments. Indoor thermal environments, occupant behaviour and heating energy consumption for new and old apartments were compared respectively. As mentioned in the review chapter two, reform and implementation of the new heating and billing system has been incorporated into new built residential apartments. It is therefore important to identify the influence of each potential factor on heating energy use finally. In this chapter the detailed information regarding results of occupant window behaviour in old apartments are compared with the results of occupant window behaviour in new apartments.

4.2 Comparison of building indoor thermal environments

According to the monitoring, the variations of mean indoor air temperature for living room and bedroom in both types of buildings are summarised in Table 4.1. During the heating period, the mean outdoor air temperature is 8.9°C with the maximum and minimum outdoor temperatures being 27.7°C and -1.9°C respectively during the investigation.

Table 4.1 The mean measured indoor air temperature of living room and main bedroom in both new and old building from 15th Feb to 15th Mar 2014

Building type	**Old building**			**New building**	
Room Type	**Living Room**	**Main Bedroom**		**Living Room**	**Main Bedroom**
Mean	22.5°C	21.5°C	**Mean**	20.7°C	19.6°C
SD	2.7°C	2.5°C	**SD**	2.3°C	2.1°C
Max	26.3°C	25.1°C	**Max**	23.7°C	22.5°C
Min	16.3°C	14.9°C	**Min**	15.6°C	15.1°C

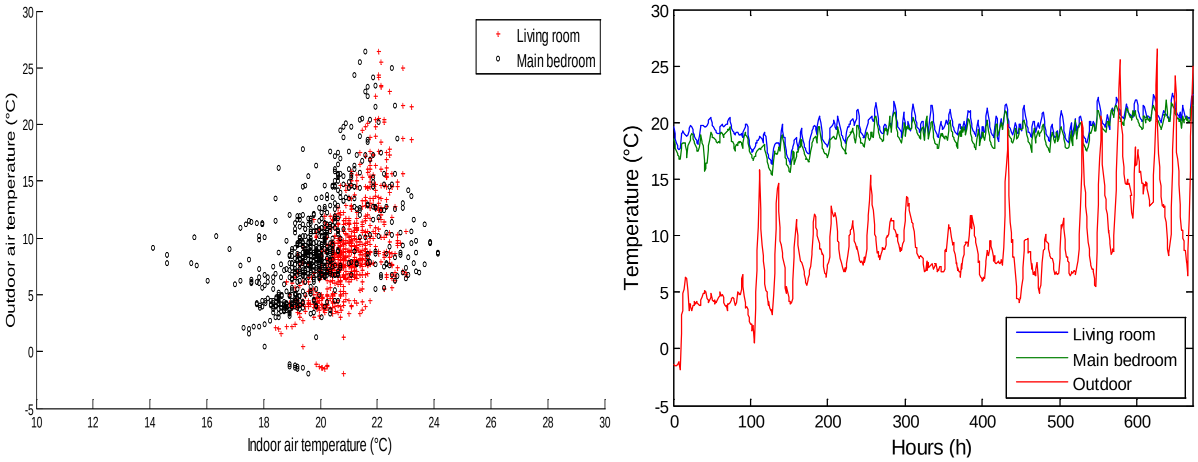
Table 4.1 shows that the mean indoor temperature of the living room in all old apartments is 22.5°C (standard deviation 2.7°C) and the indoor air temperature in new ones is 20.7°C (standard deviation 2.5°C) which is respectively 1.8°C lower than

the value measured in old apartments. Meanwhile the mean indoor air temperature is 21.5°C(standard deviation 2.3°C) in main bedroom of old traditional building and 19.6°C (standard deviation 2.1°C) in new buildings which is respectively 1.9°C lower than that in old one. The value of the indoor air temperature depends on the two different types of apartments and operated heating control systems. From the comparison, it could be found that both the living room and the bedroom temperatures in the old apartments are higher than those in the new apartments, agreeing with previous field experiments study. The pervious study carried out the results of indoor air temperature of living room for old traditional distract heating residential apartments in Beijing. Cao, et al compared indoor thermal environments and thermal comfort in two groups of residential apartments, one group of traditional central heating without any control and another one group of new individual boiler heating with control. They measured the mean indoor air temperature of old apartments were 0.5-3.0°C higher than that of new apartments (Cao, et al., 2014). This may reflect that in the new apartments, occupants prefer a lower indoor temperature to reduce heating energy consumption, as indoor temperature has been popularly used to reflect occupants' indoor temperature settings in winter in existing studies (Wei, et al., 2014).

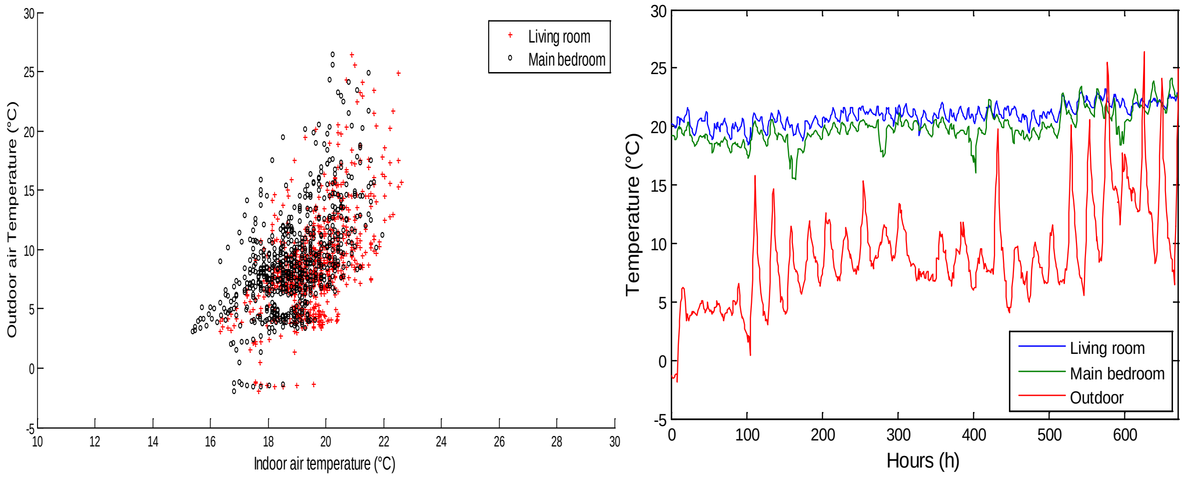
Occupants can adjust their thermal environment based on their own local requirement via convenient and effective system of control (i.e. operable windows or local temperature control) (Nicol & Humphreys, 2007). What follows is a discussion on the potential reasons for the discrepancy in these results. As mentioned before, occupants can adjust the TRVs of heating set-point in order to satisfy their needs for indoor environment in new apartments. In addition, occupants have possibility to reduce indoor temperature and heating energy use by adjusted TRVs in each radiator in new apartments. However occupants do not have any control devices of heating in old apartments, they only can open the window or door to adjust the indoor air temperature if the rooms were overheated, in addition, the indoor temperature in old apartments are significantly higher than that in new ones.

4.2.1 Connection of indoor and outdoor temperature in old apartments

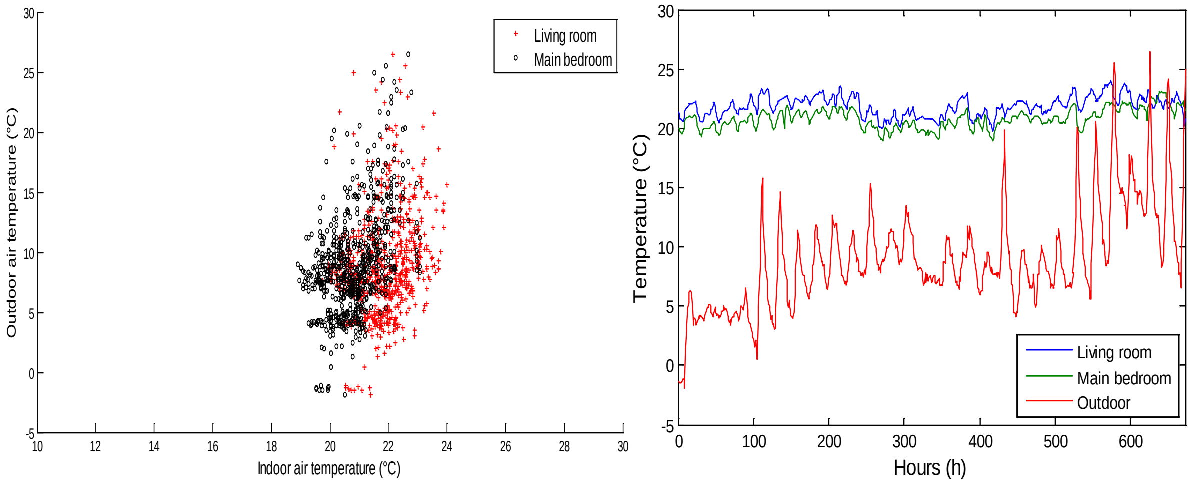
For heated buildings, the indoor temperature depend on outdoor temperature, it is different from naturally ventilated buildings (Humphreys, et al., 2010). The analysis of indoor temperature dependent on outdoor temperature shown in Figure 4.1 describes the indoor temperature in living room and main bedroom changed with outdoor temperature in each old apartment. The correlation between indoor temperature and outdoor temperature have also been found by Yan et al, they found that the indoor temperature increased with outdoor temperature dropped when the outdoor temperature is below 10°C in Chinese dwellings during heating season period (Yan, et al., 2016). In Figure 4.1 reveals generally the indoor temperature in both living and bedroom in each old apartment maintain the temperature from 19-23°C when outdoor temperature maintain the temperature from 5-15°C. Old apartments have no direct control for occupants and thus they can only open the window to adjust their thermal environment. The observations indicates that the trend of indoor temperature is generally changed with outdoor temperature, this is can be likely explained by two reasons, one is the insulation level is worse for old building compared with new building. Thus it more likely can be affected by outdoor environment. Another is the indoor temperature in old apartments is higher than that in new apartments, occupants prefer to open window to decrease indoor temperature when overheating in rooms. The correlation between window opening behaviour and indoor air temperature will to be discussed in following section.



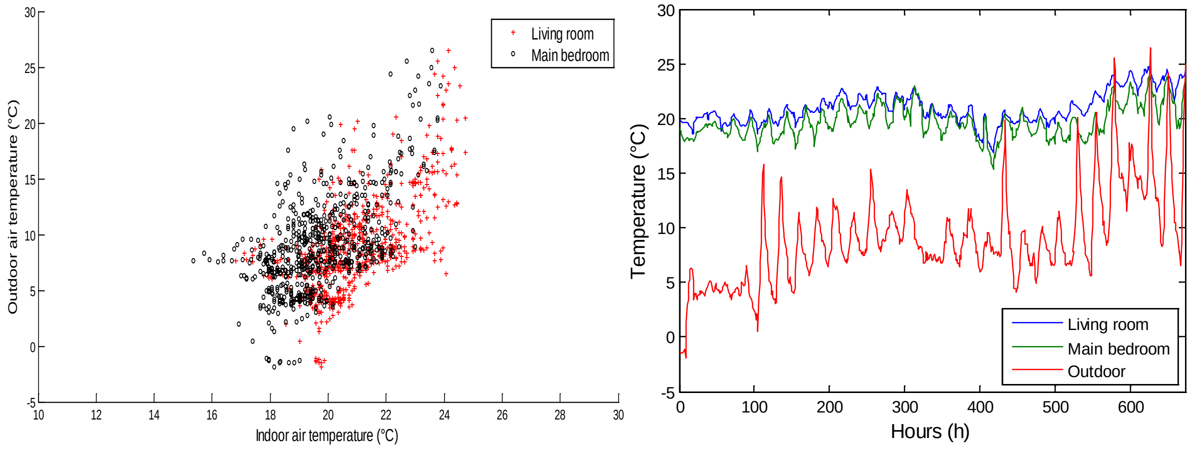
Old apartment 1



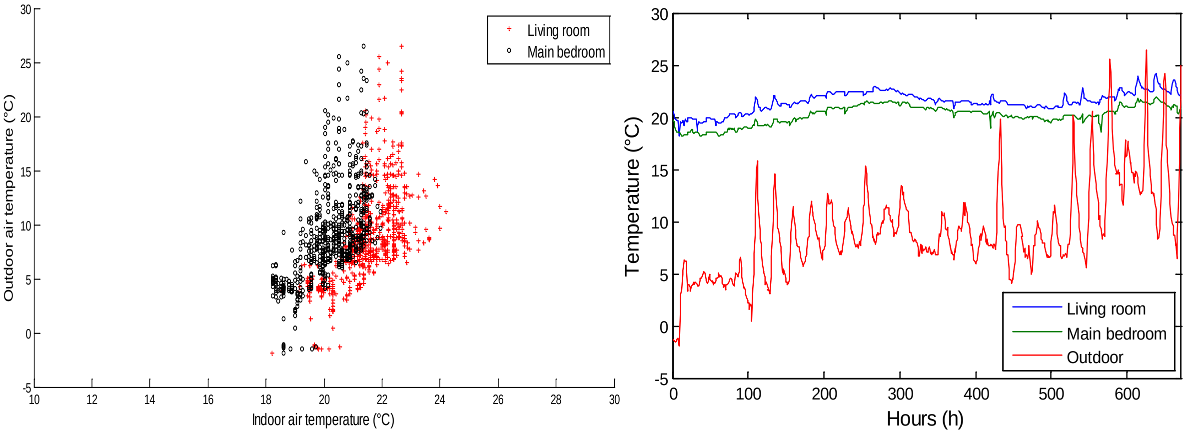
Old apartment 2



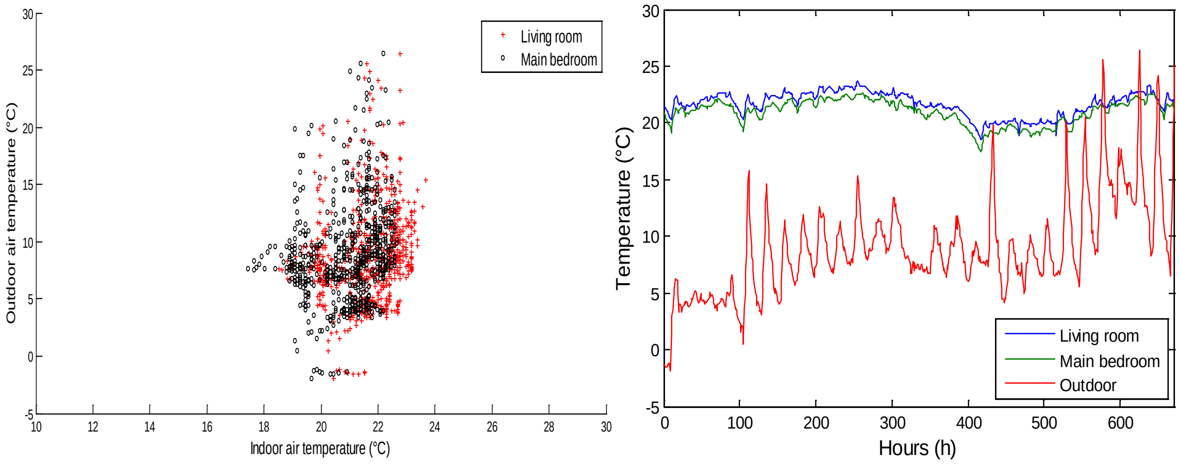
Old apartment 3



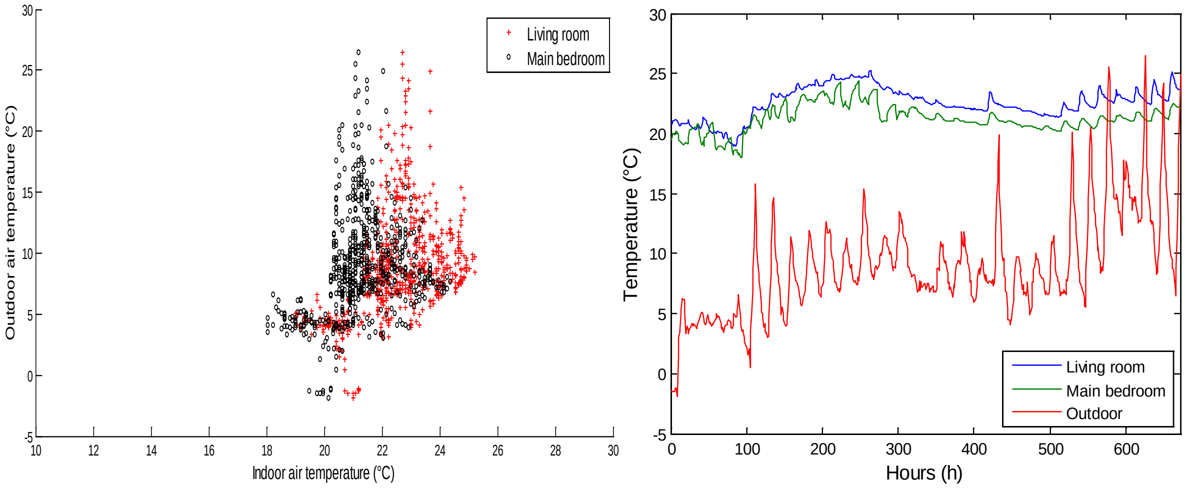
Old apartment 4



Old apartment 5



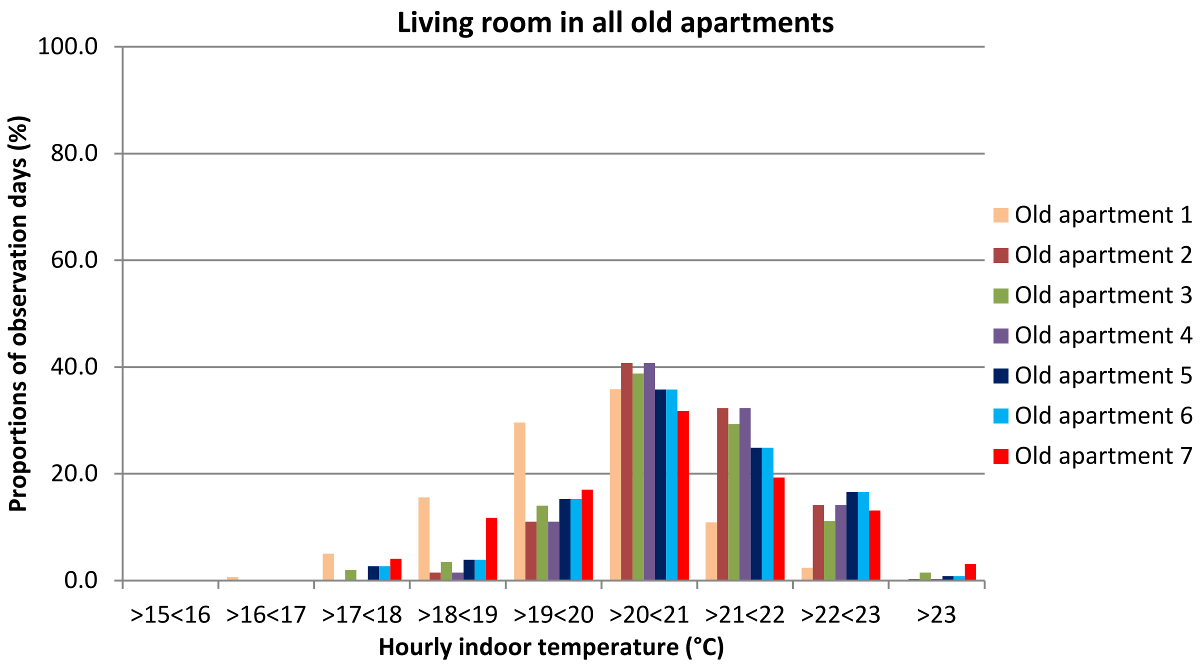
Old apartment 6



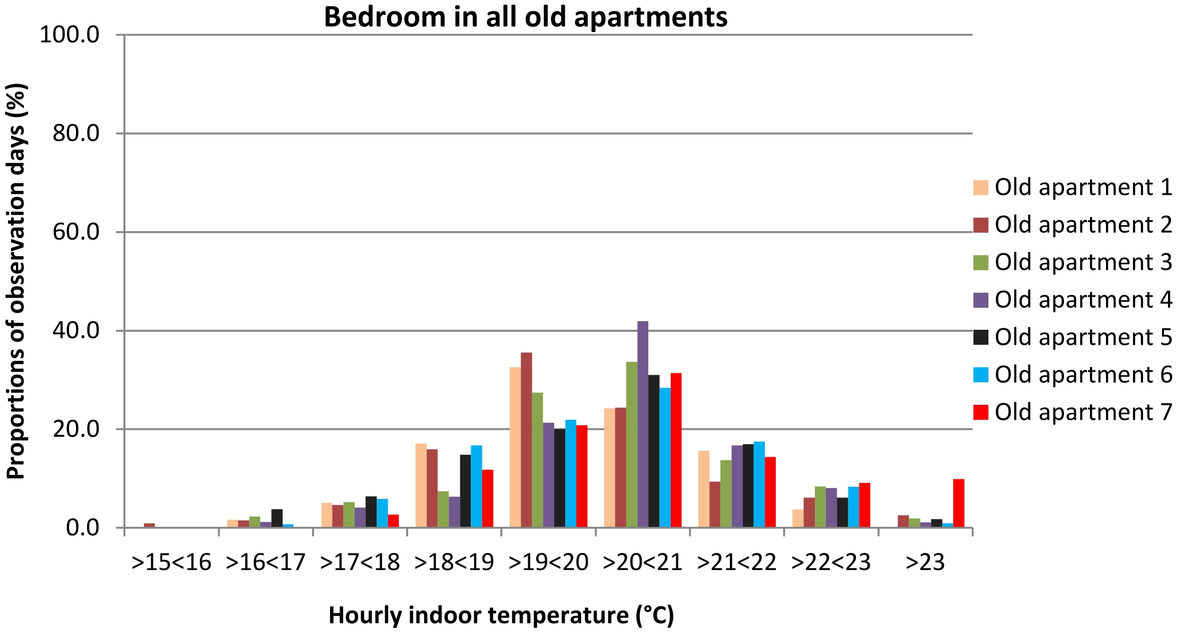
Old apartment 7

Figure 4.1 Scatter-plot of indoor and outdoor air temperature in all old apartments

Figure 4.2 indicates the binned hourly indoor temperature in living room and bedroom for all old apartments from 08:00am to 18:00pm, and it gives a diagram of indoor conditions during investigated periods in this study. In order to estimate confidence in results, each temperature bin includes all observed days during heating periods. From figure 4.2, it was observed that in general, indoor temperature in living room and main bedroom in each old apartment. The measured results of indoor temperatures reflect that the around 80% in both living room and bedroom between 20 to 22°C. The figure 4.2(a) also reflects that there are approximately 16% of indoor temperatures above 22°C in living room for all old apartments. The indoor temperatures in main bedroom contain approximately 12% above 22°C for all old apartments shown in figure 4.2(b).



(a)

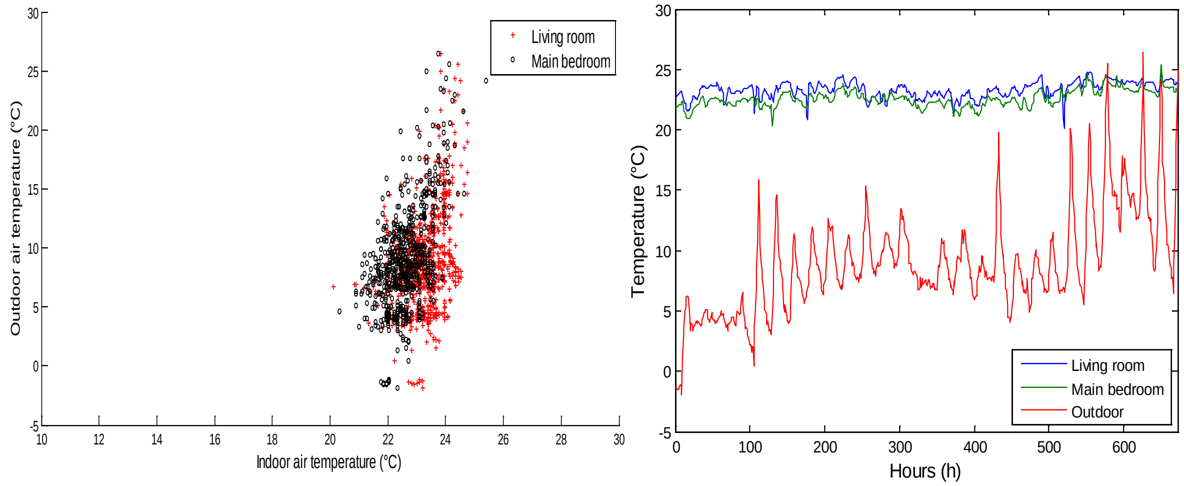


(b)

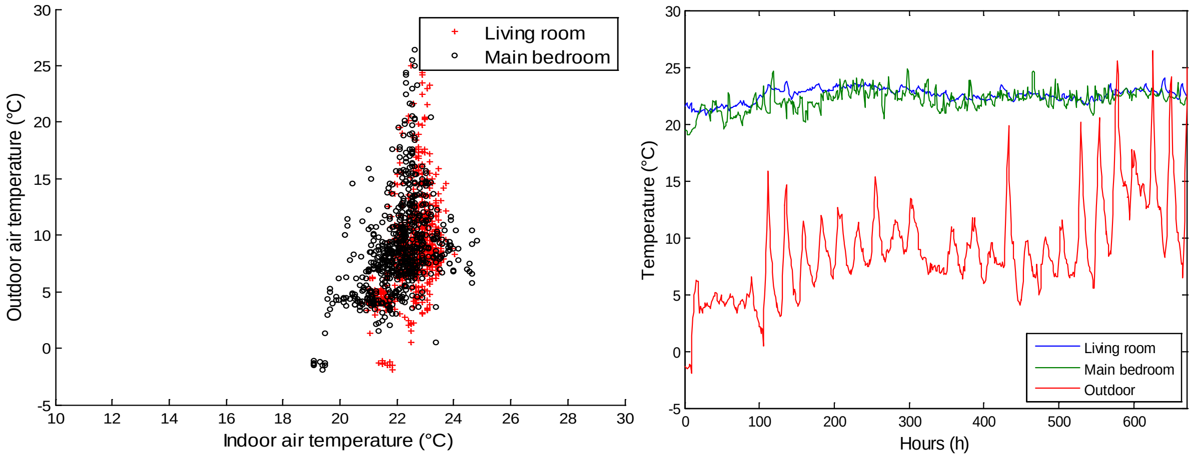
Figure 4.2 The binned hourly indoor temperature in living room and bedroom of all old apartments during observation period

4.2.2 Connection of indoor and outdoor temperature in new apartments

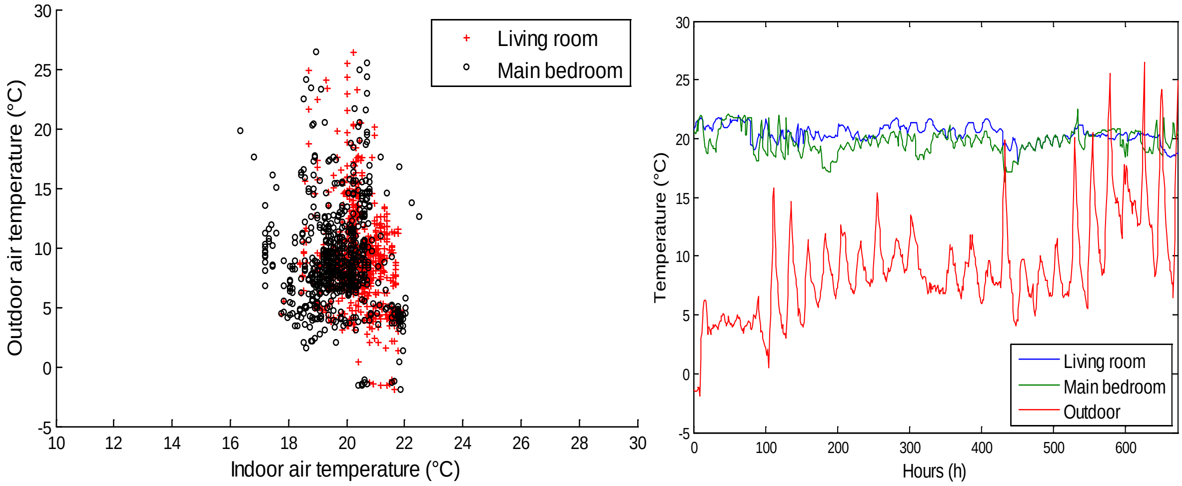
The analysis of indoor temperature dependent on outdoor temperature shown in Figure 4.3 describes the indoor temperature in living room and main bedroom changed with outdoor temperature in each new apartment. In Figure 4.3 reveals generally the indoor temperature in both living and bedroom in each apartment maintain the temperature from 18-22°C when outdoor temperature maintain the temperature from 5-15°C. New apartments have direct control for occupants and thus they can use TRVs to adjust their thermal environment. The observations indicate that the deceases indoor temperature is changed with outdoor temperature increased. This is can be likely explained by the occupants in new apartments preferred to stay in a cooler indoor environment due to the higher outdoor temperature. In addition, indoor temperatures in new apartments are lower than that in old apartments and occupants can use TRVs to decrease indoor temperature when overheating in rooms. Figure 4.3 depicts indoor air temperature in bedroom responds inconsistently to that in living room for apartment 3. In this example, the air temperature in bedroom decreases with outdoor temperature increased. The reason for this can be explained that when TRVs altered in bedroom to keep indoor temperature between 19 to 21°C. Furthermore, the correlation between window opening behaviour and indoor air temperature will to be discussed in following section.



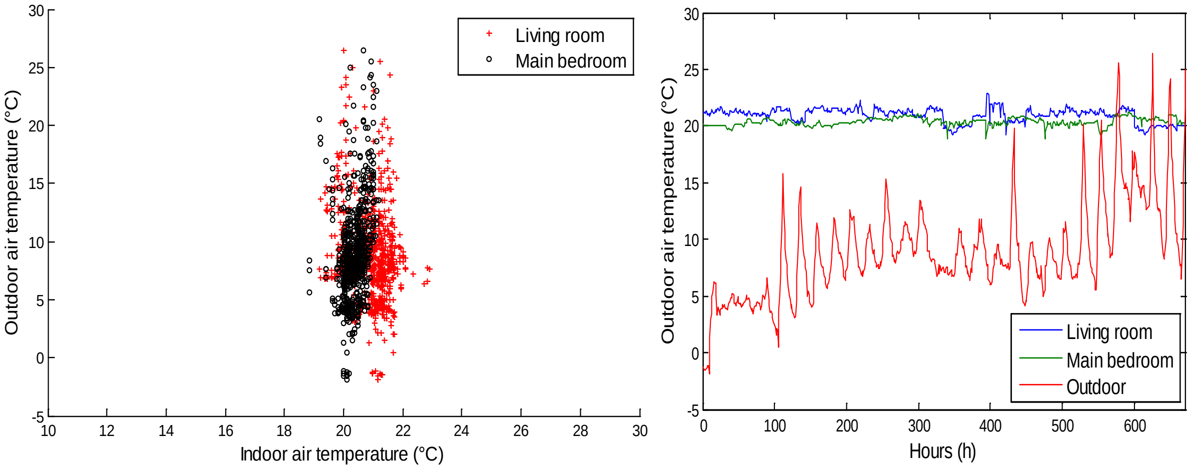
New apartment 1



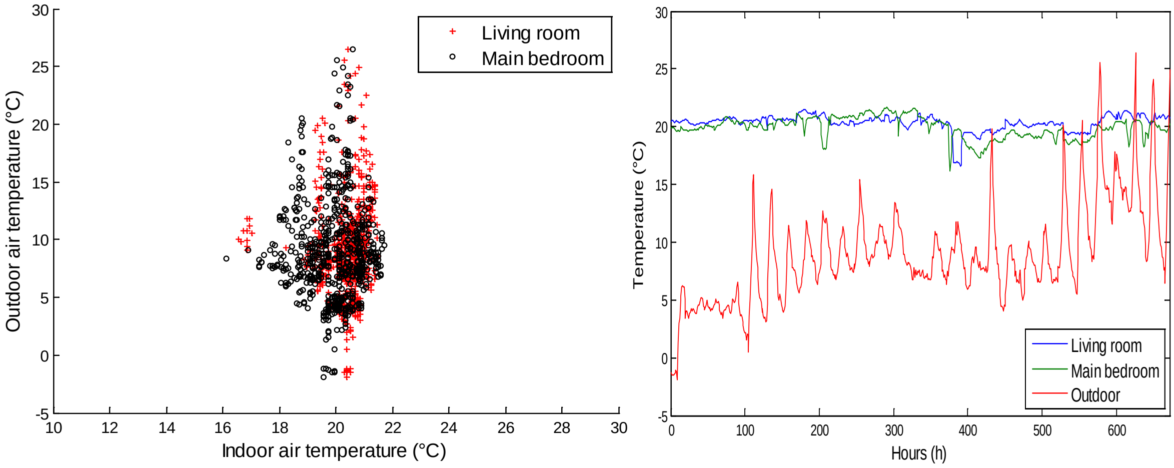
New apartment 2



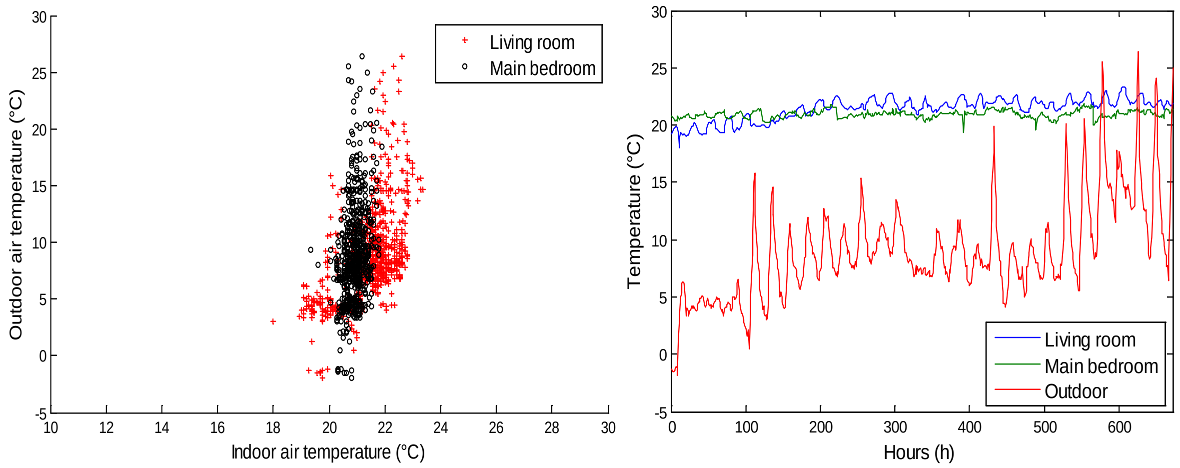
New apartment 3



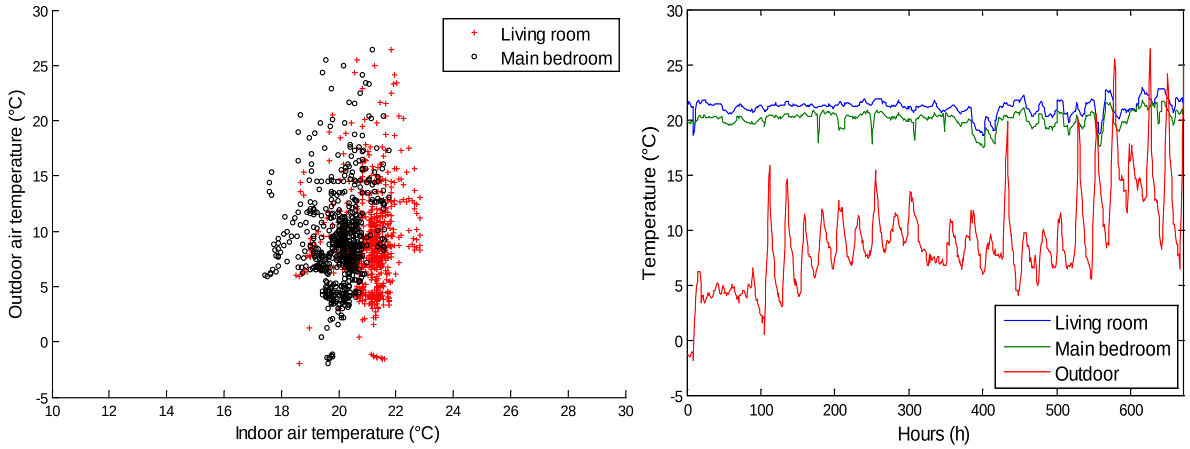
New apartment 4



New apartment 5



New apartment 6



New apartment 7

Figure 4.3 Scatter-plot of indoor and outdoor air temperature in all new apartments

Figure 4.4 indicates the binned hourly indoor temperature in living room and bedroom for all new apartments from 08:00am to 18:00pm, and it gives a diagram of indoor conditions during investigated periods in this study. In order to estimate confidence in results, each temperature bin includes all observed days during heating periods. From figure 4.4, it was found that the measured results of indoor air temperatures reflect that the around 60% in both living room and bedroom between 19 to 21°C. The figure 4.4(a) also reflect that there are less proportion of indoor temperatures above 22°C in living room for all new apartments compared with old ones. The indoor temperatures in living and main bedroom for all new apartments contain approximately 2% above to 23°C shown in figure 4.4(b).

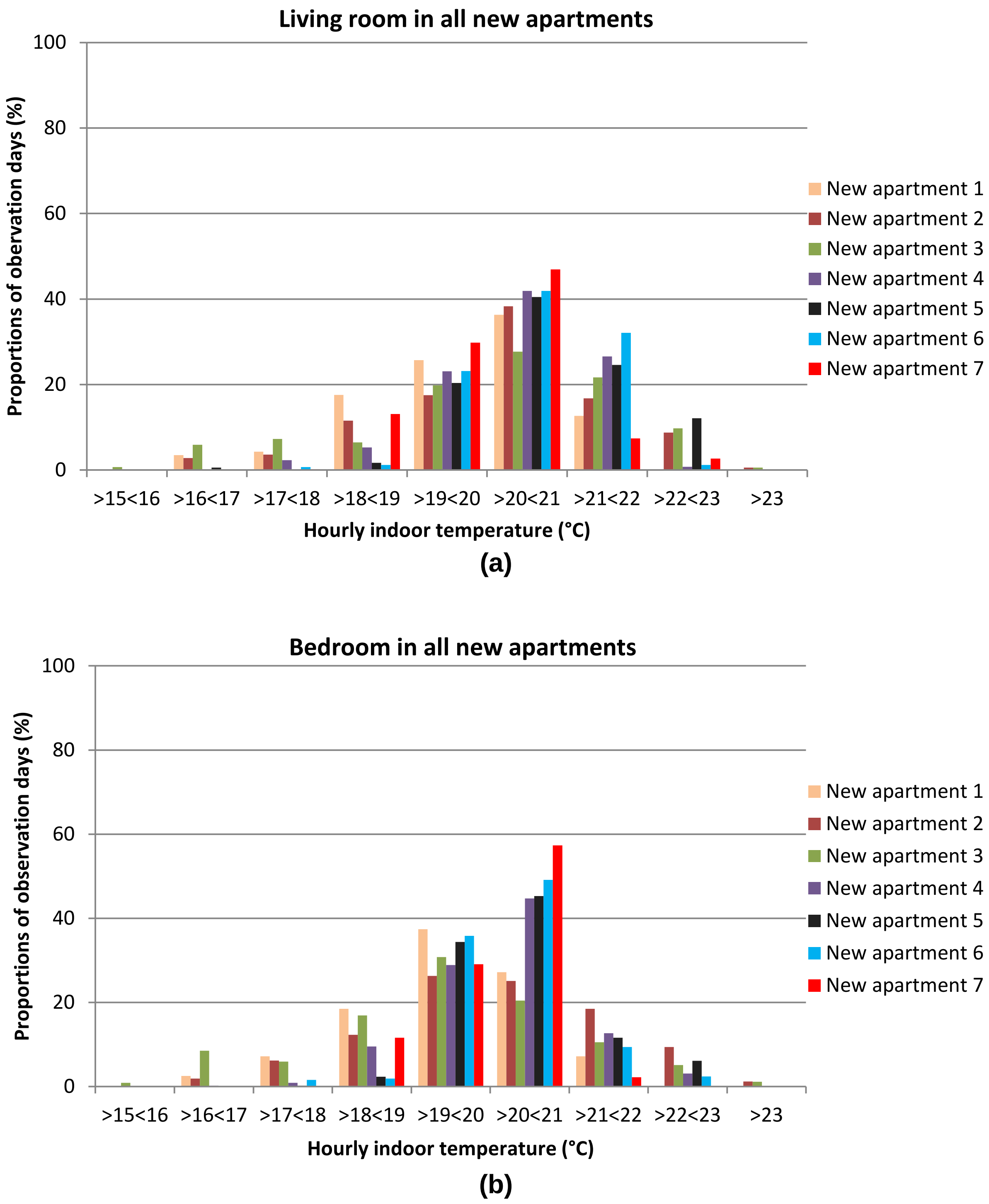


Figure 4.4 The binned hourly indoor temperature in living room and bedroom of all new apartments during observation period

4.3 Occupants' window behaviour

It is important to identify occupant window behaviour effect on operational energy use in residential buildings. Occupants' window behaviour has effect on energy consumption (Andersen, et al., 2009). Therefore, occupants' window behaviour in the two types of investigated apartments is compared in this section. Previous studies have carried out window opening behaviour of occupants and the influencing factors that influence on occupants' control in residential buildings. The outdoor temperature were found to be one of most important factors related to window opening, additionally, season, time of day, orientation of windows and type of rooms are the main parameter impact on occupants' window operation in residential buildings (Fabi, et al., 2012; Dubrul, 1988). As mentioned in section 3.3, the outdoor temperature was collected by data logger. The window state was monitored every one minute by a pair of window contactors and the change of window states. It was recorded in binary form (i.e. open is 1; closed is 0). In the study, the parameter used to reflect occupants' window behaviour is the proportion of time during the monitoring period when the window is opened. The overall field measured data reflect that the windows in all old apartments were opened for 54% of the monitoring time, while they were opened only for 29% of the monitoring time in all new apartments. Thus the relationship between window opening behaviour and indoor and outdoor temperature in each apartment can be evaluated further as follow.

4.3.1 Relationship between weather factors and window opening behaviour

4.3.1.1 Indoor temperature effect on the window operation in old apartments

Previous study represented that the indoor temperature is one of most important factors related to window opening in residential buildings (Fabi, et al., 2012). Thus the relationship between window opening behaviour and indoor temperature can be evaluated further as follow. Figure 4.5 describes in old apartment 1, the correlations between the proportions of window opening and indoor air temperature in living and main bedroom analysed by Probit regression model. It was found that the proportions of window opening increases with indoor air temperature increased in both living room and main bedroom. Proportions of window opening rise approximately to 40% at 22°C of living room in old apartment 1. Proportions of window opening reach to 37% at 22°C of bedroom in old apartment 1. Figure 4.9 show that probability of window opened in both living and bedroom account for around 35% when indoor temperature around at 23°C in old apartment 5.

Overall, Figure 4.5 to 4.11 reflects that indoor temperature increased from 15 to 20°C, the more windows opened obviously by occupants. For all old apartments, the proportion of windows opening strongly related to indoor temperature in both living room and main bedroom. Figure 4.8 reflect that the proportions of window opening rise from 20 to 40% when indoor temperature increased from 18 to 24°C in old apartment 4. The inferred probability of open window in old apartments varied as a function of the indoor air temperature. There was a significate increase in the probability as the indoor temperature increased. It suggesting that indoor temperature was a significant predictor.

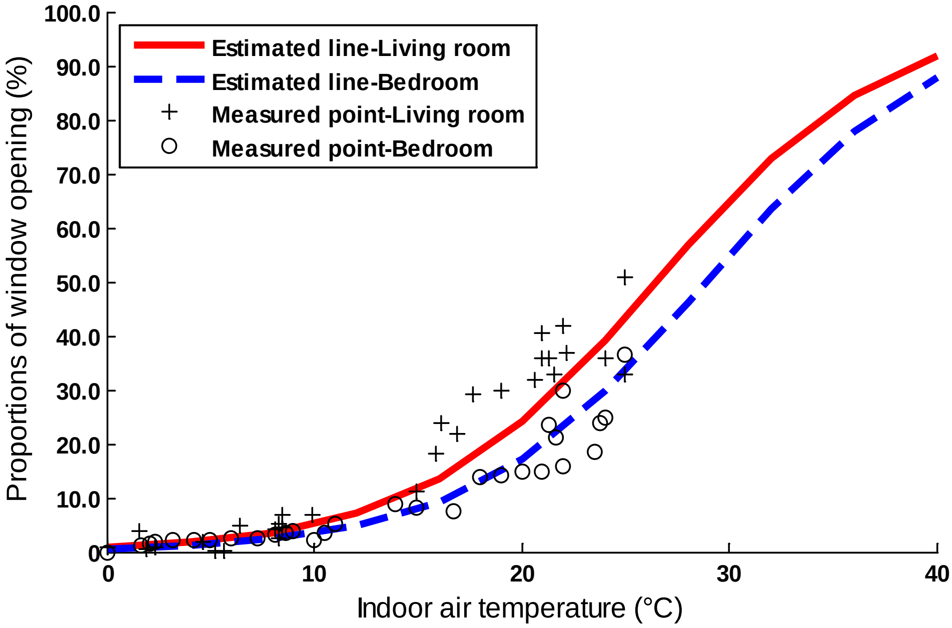


Figure 4.5 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 1

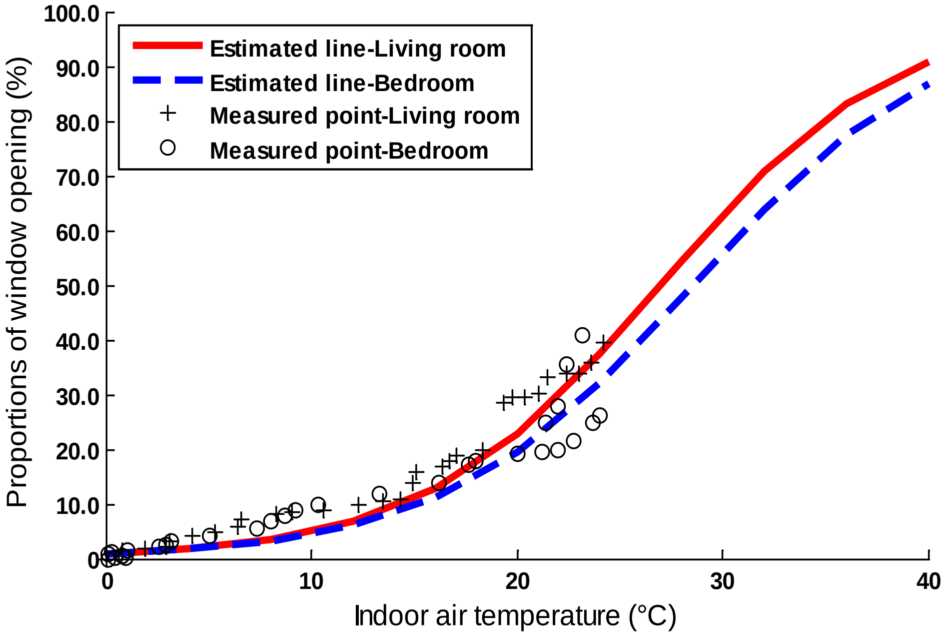


Figure 4.6 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 2

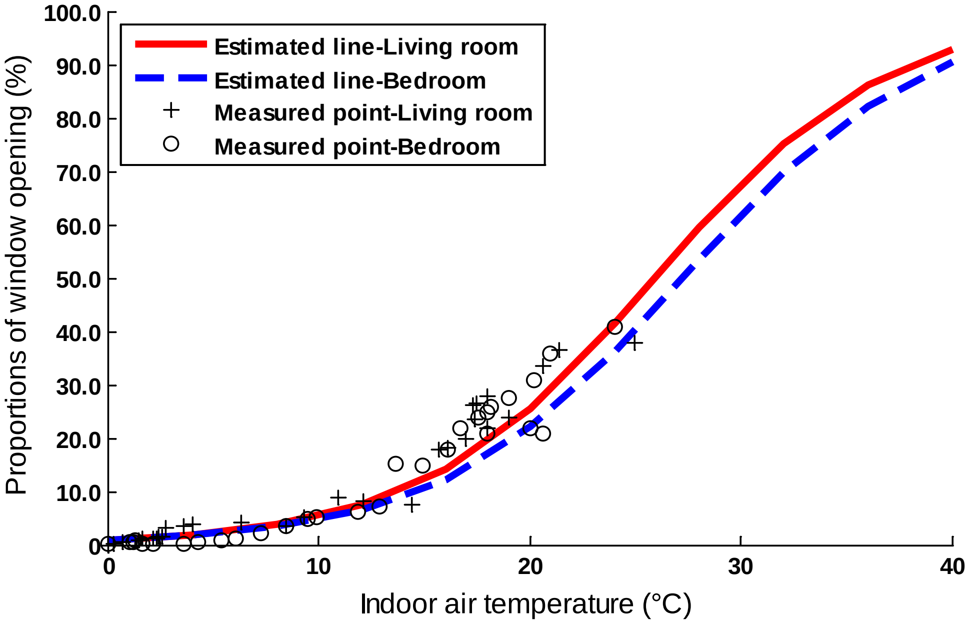


Figure 4.7 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 3

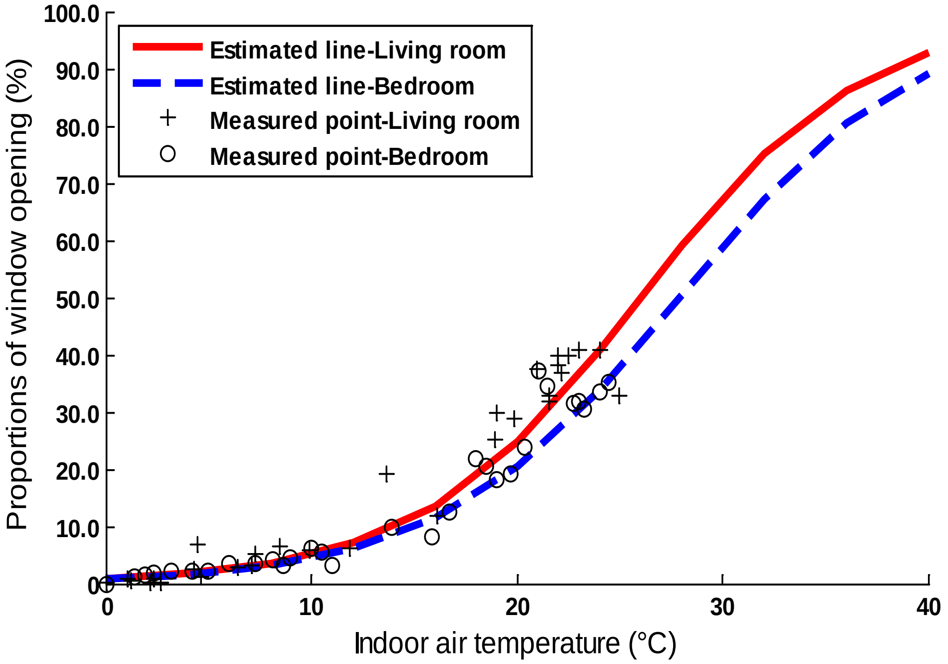


Figure 4.8 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 4

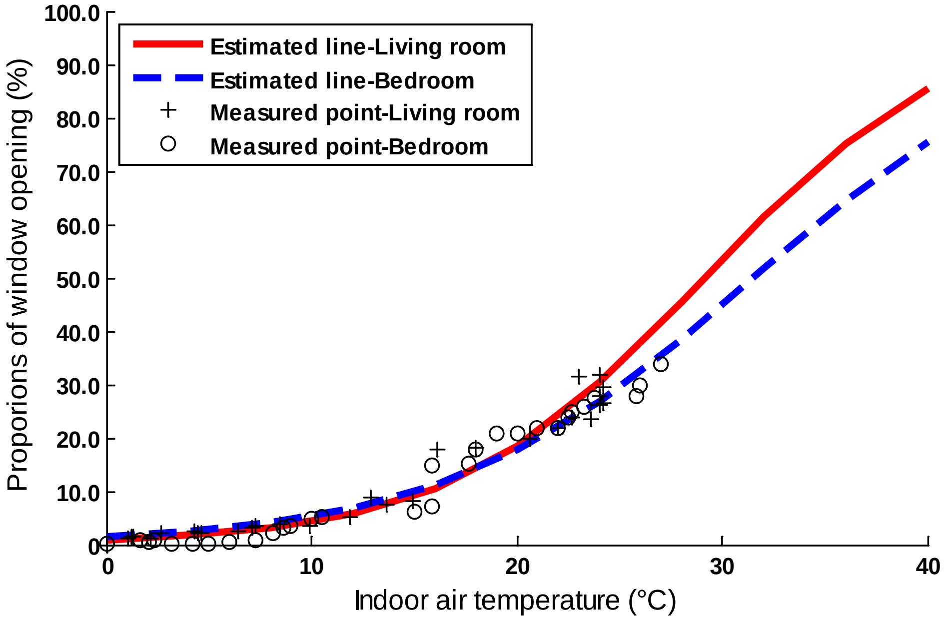


Figure 4.9 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 5

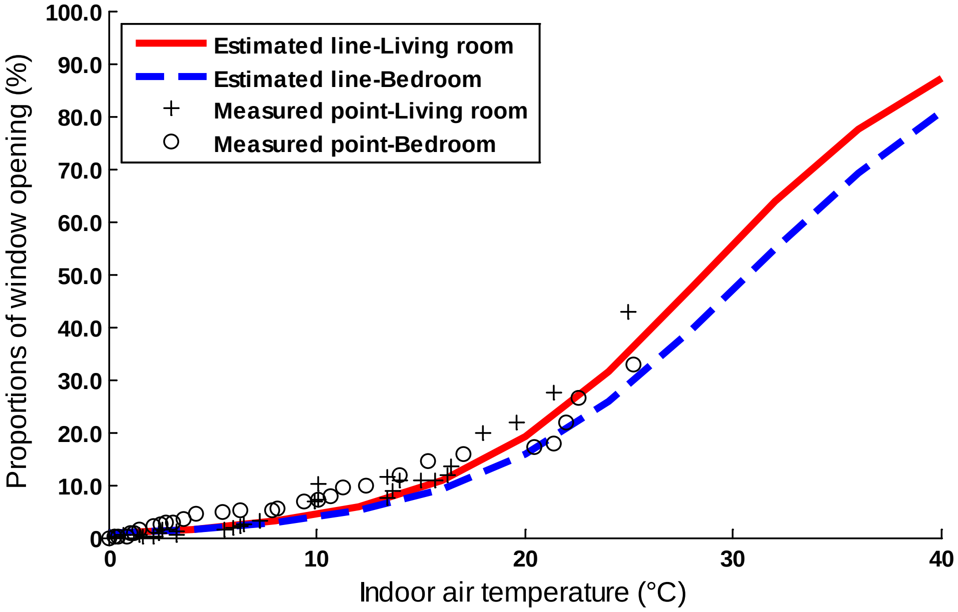


Figure 4.10 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 6

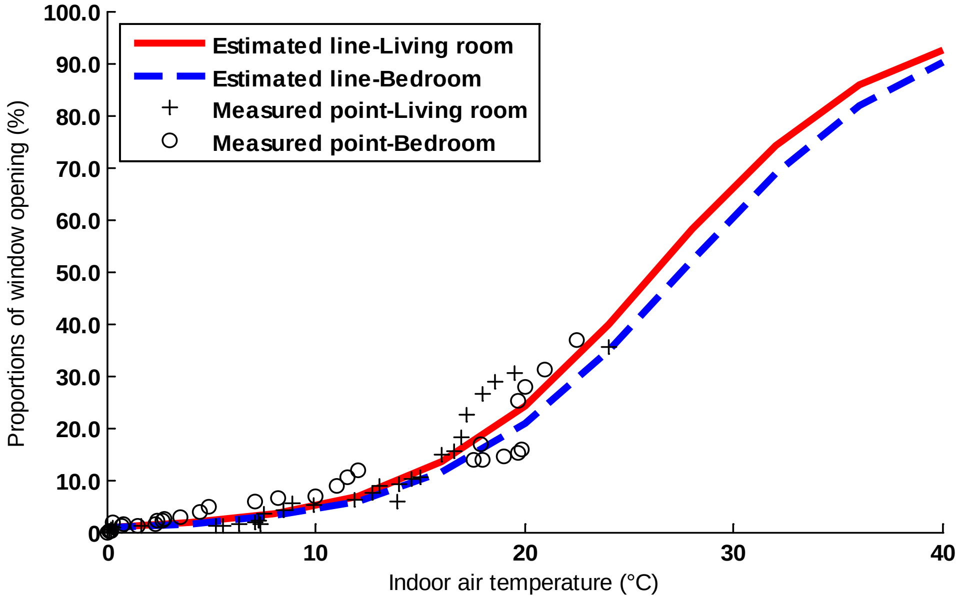


Figure 4.11 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in old apartment 7

4.3.1.2 Indoor temperature effect on window operation in new apartments

Previous study represented that the correlation between indoor temperature and occupants' window behaviour and it is one of most important factors related to window opening in residential buildings (Fabi, et al., 2012; Dubrul, 1988). Thus the relationship between window opening behaviour and indoor temperature in living and bedrooms can be evaluated further as follow.

Figure 4.12 describes in new apartment 1, the correlations between the proportions of window opening and indoor air temperature in living and main bedroom analysed by Probit regression model. It was found that the proportions of window opening increases slightly with indoor air temperature increased in both living room and main bedroom. Proportions of window opening rise approximately to 18% at 20°C of living room in old apartment 1. Proportions of window opening reach to 16% at 20°C of bedroom in old apartment 1. For new apartment 2, the proportion of windows open is not very strongly related to indoor temperature in both living room and main bedroom. Probability of window opened in both living and bedroom account for around 8% at 19°C in Old apartment 2(Figure 4.13). For all new apartments, the proportion of windows open slightly related to indoor temperature in both living room and main bedroom. Figure 4.17 describe that proportion of window opened in both living and bedroom rise from 6 to 10% when indoor temperature rise from 15 to 20°C in old apartment 6.

In general, Figure 4.12 to 4.18 reflects that indoor temperature increased, the more windows opened slightly by occupants. The inferred probability of open window in new apartments varied little as a function of the indoor temperature. There was a slight increase in the probability as the indoor temperature increased. This is maybe because the occupants prefer to use heating control system to adjust indoor environment based on their actual habit. Further analysis in section 4.3.2, represented the most reasons of opening window were ventilate to fresh air into apartments.

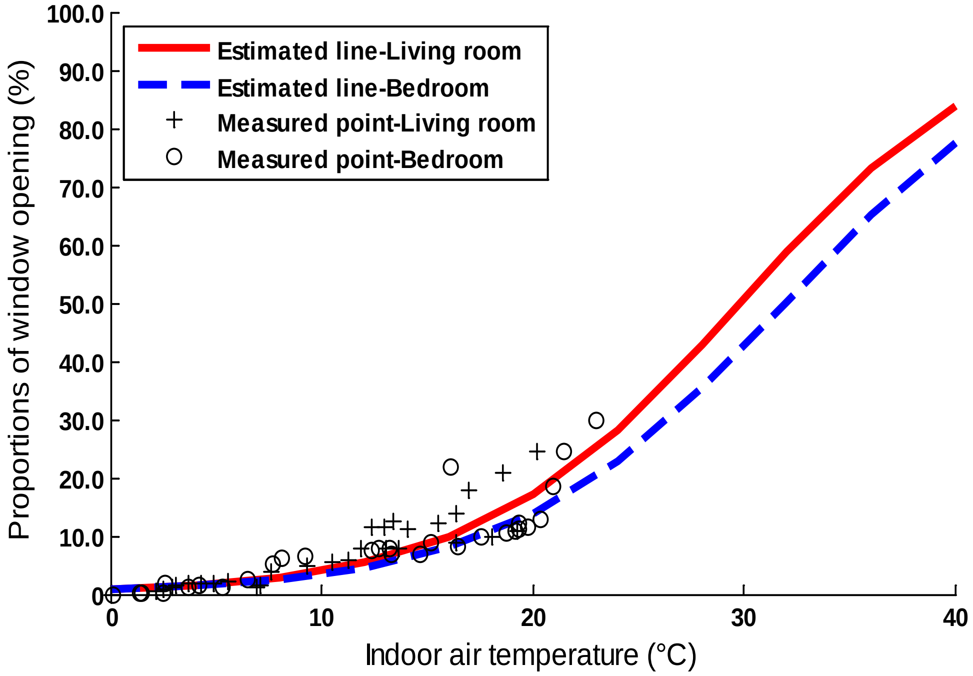


Figure 4.12 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 1

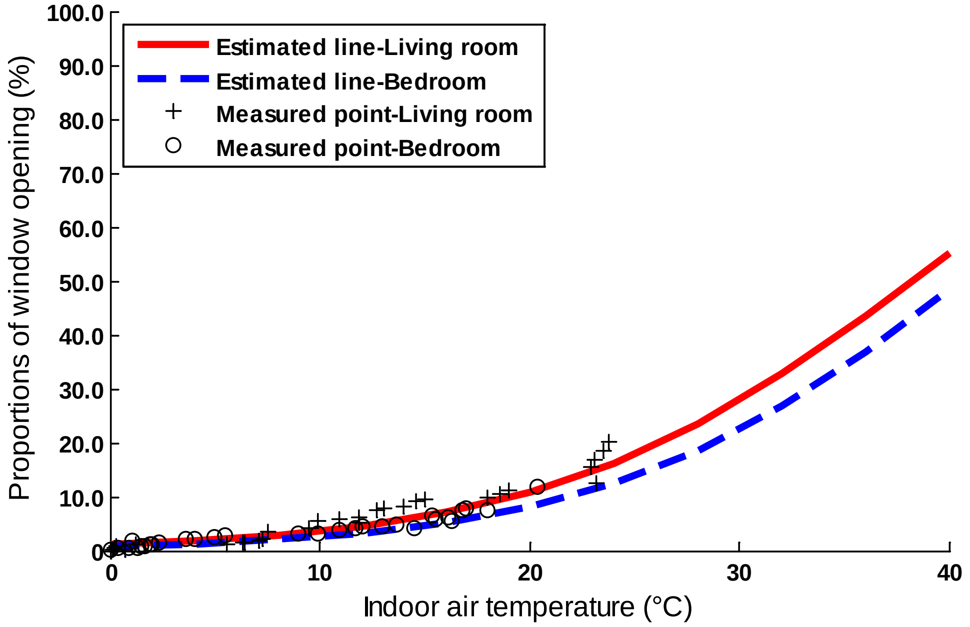


Figure 4.13 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 2

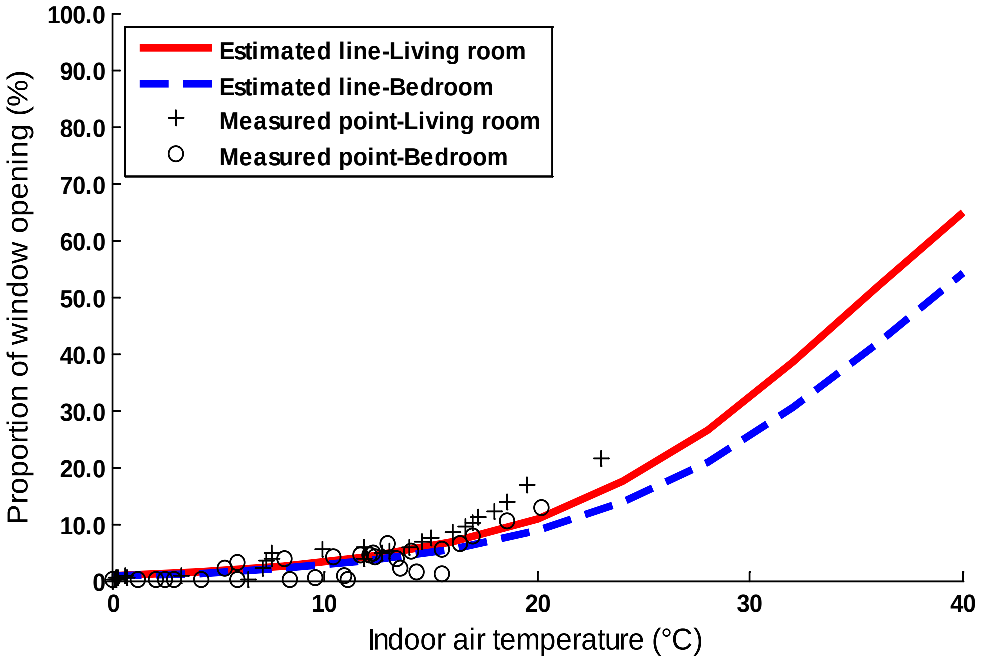


Figure 4.14 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 3

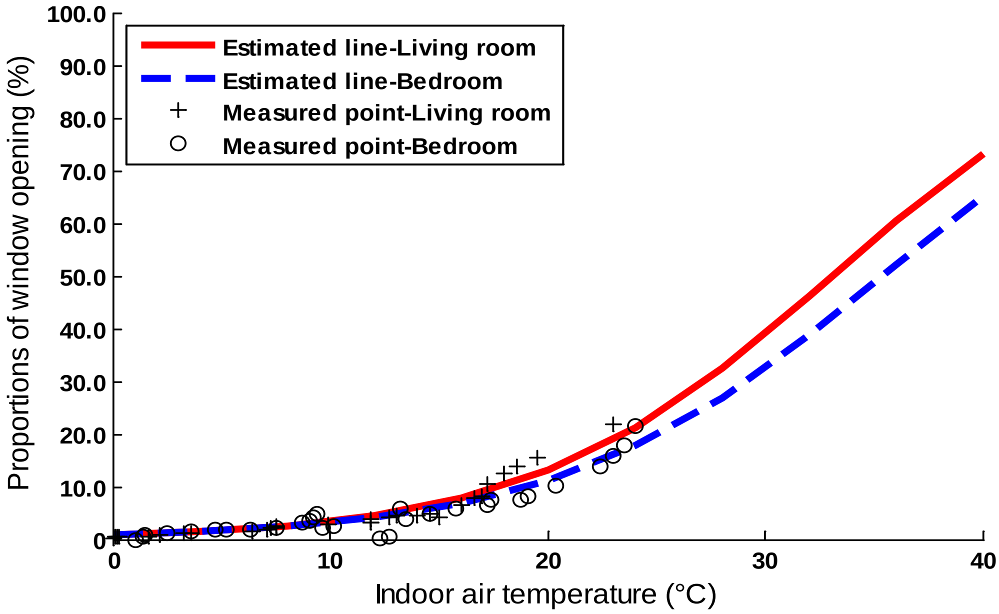


Figure 4.15 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 4

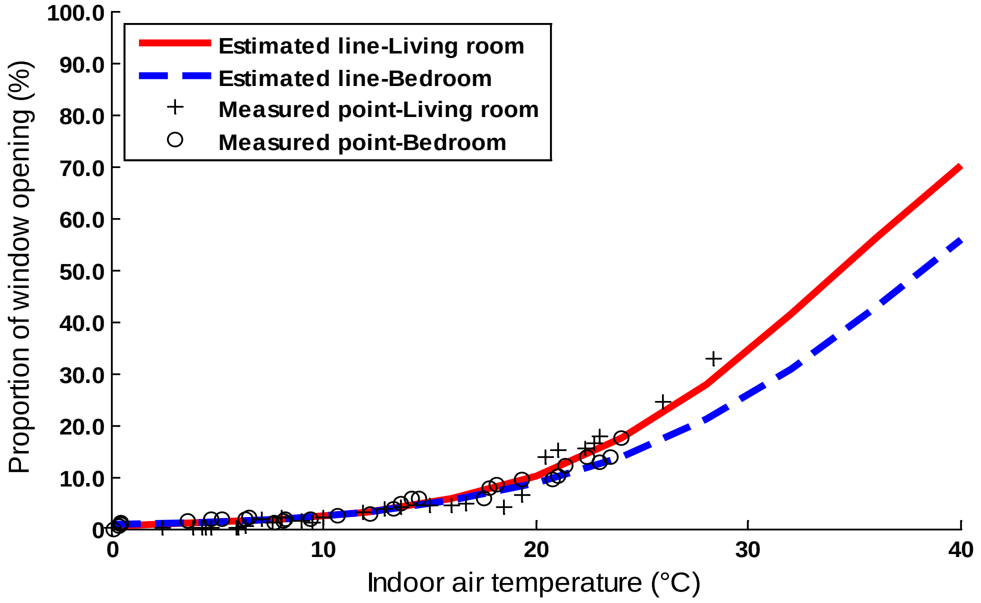


Figure 4.16 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 5

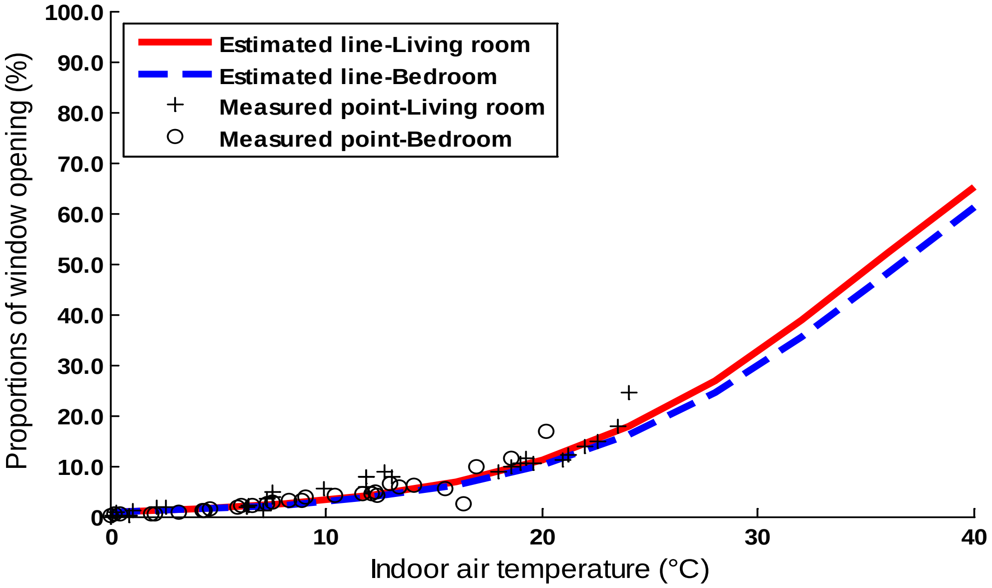


Figure 4.17 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 6

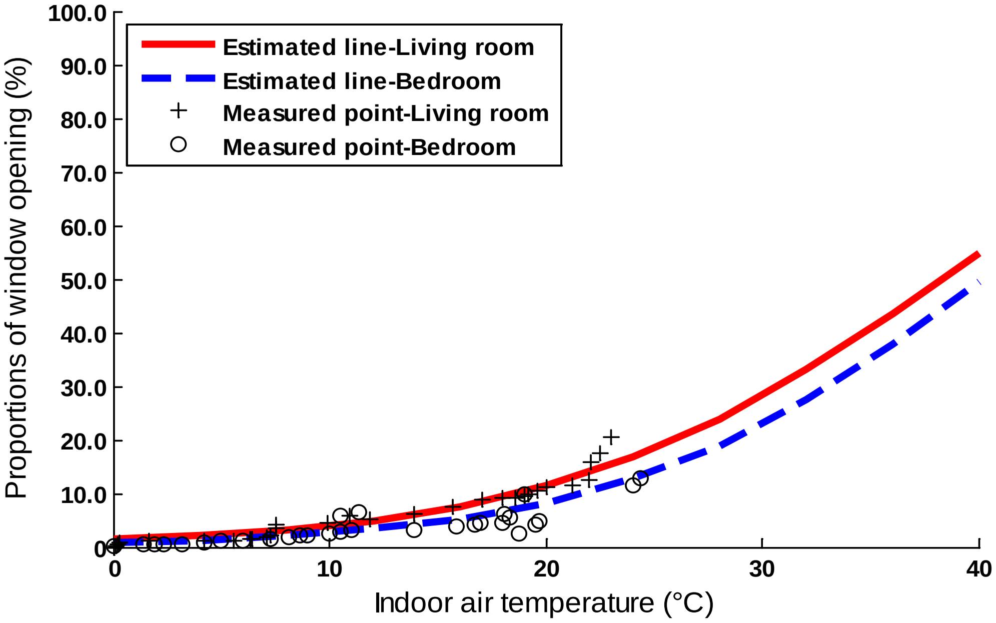


Figure 4.18 Logistic regression curve for window open as a function of the indoor air temperature in living room and bedroom in new apartment 7

4.3.1.3 Outdoor temperature effect on window operation

In the study, the parameter used to reflect occupants' window behaviour is the proportion of time during the monitoring period when the window is open. During morning time, the most reasons for window opening in both new and old apartments were that the occupants wanted to bring in more fresh air. According to the results of questionnaires, in old apartments, another significant reason for open windows implies that the majority of occupants respond that the windows were opened because it was hot inside apartments and they prefer to have cooler indoor environments. Whilst some occupants in new apartments respond that they prefer to leave windows closed to reduce heat loss, in particular in sunny day and outdoor temperature increased. Furthermore, analyses of reason for opening windows are discussed in next section. Therefore, it is important to identify that the correlations of outdoor temperature and proportion of window opening in both new and old apartments.

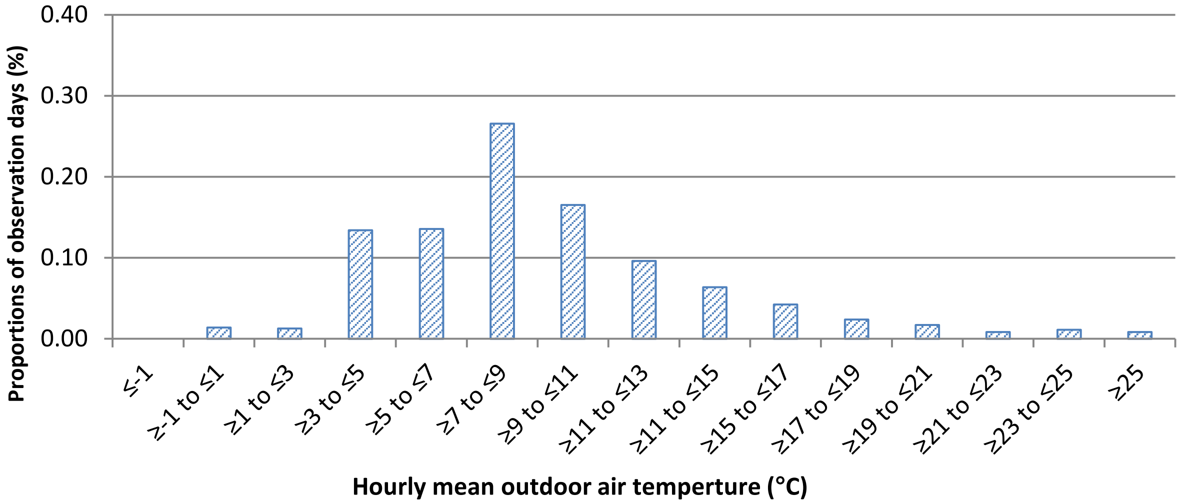


Figure 4.19 The binned hourly mean outdoor temperature from 08:00 to 24:00 observation period

Figure 4.19 indicates the binned hourly outdoor temperature from 08:00 to 24:00, and it gives a diagram of outdoor conditions during investigated periods in this study. In order to estimate confidence in results, each temperature bin includes all observed days during heating periods. In order to identify if the window opening behaviour in all new apartments is different from all old apartments have been explored. It is important to determine the relationship between the observed window opening behaviour and outdoor air temperature. Important statistical properties of two logistic regression models are closed (coded as 0) and open (coded as 1). The logistic regression analysis of window open in longitudinal monitoring of Figure 4.20 describe the probability of open window as function of the outdoor air temperature in new and old apartments. As previous study found that the proportion of windows open strongly related to temperature. In Figure 4.20 the new apartment model with the observed proportions of window left open against outdoor temperature is plotted on the top and the old apartment model is plotted on the bottom. The scatters plotted with the actual response of observation window left open during whole monitored periods. The correlation between the predicted proportions of open window and outdoor temperature have also been used by Nicol and Humphreys, they found similar relationship in Danish dwellings (Nicol & Humphreys, 2004). There is clearly difference between old and new apartments. The proportions of window opening in new apartments are generally lower than that in the old apartments. Comparisons in figure 4.20, it plot that the occupants in old apartments opening windows in consistent with increases outdoor temperature (Raijal, et al., 2007). This is maybe because outdoor temperature with higher solar radiation, the indoor temperature increased, the more windows opened by occupants. It is important to note that there are significate correlations between outdoor temperature and window opening in old apartments. The inferred probability of open window in new apartments varied little as a function of the outdoor temperature, suggesting that outdoor temperature was not a significant predictor. There was a slight increase in the probability as the outdoor temperature increased. This could be an effect of new heating control systems and heating payment, which is describe in sections 4.4.

The proportions of window opening in living room and bedroom for old apartment are given by:

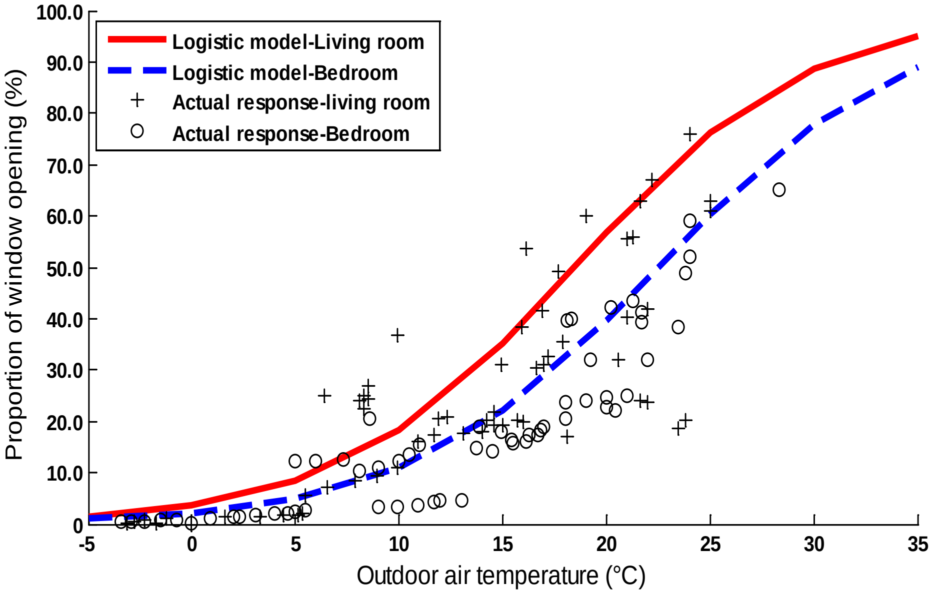
$$p\text{-Living room} = \exp(-3.285+0.178*T_{out})/[1+\exp(-3.285+0.178*T_{out})]*100$$

$$p\text{-Bedroom} = \exp(-3.785+0.168*T_{out})/[1+\exp(-3.785+0.168*T_{out})]*100$$

The proportions of window opening in living room and bedroom for new apartment are given by:

$$p\text{-Living room} = \exp(-4.185+0.148*T_{out})/[1+\exp(-4.185+0.148*T_{out})]*100$$

$$p\text{-Bedroom} = \exp(-4.313+0.139*T_{out})/[1+\exp(-4.313+0.139*T_{out})]*100$$



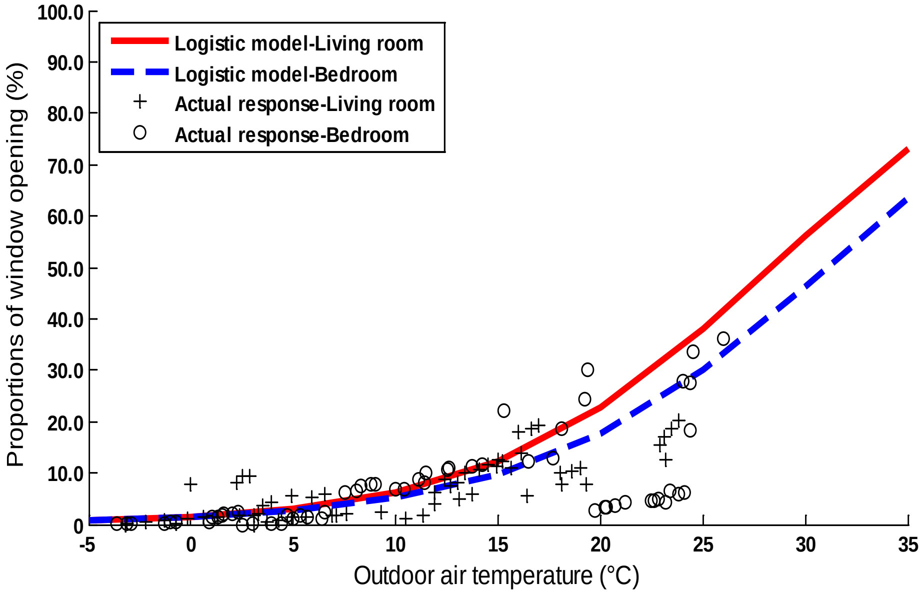


Figure 4.20 Logistic regression curve for window open as a function of the outdoor air temperature in old apartments (top) and new apartments (bottom)

4.3.1.4 Time of day effect on window opening

The investigations revealed that the majority of occupants are absented from morning 9am to 6pm regularly during the weekdays. It is therefore time of day was divided into five main time phase, given in table 4.2. Phase one (T1) is from beginning of day 00:00am to 7:00am, because the occupants normally fall sleep during this period of times. Phase two (T2) is from 7:00am to 9:00am during morning time when they wake up until left to work. Phase three (T3) is from 9:00am to 18:00pm, because occupants start to work until finish work and come back to home during this period of times. Phase four (T4) is from 6:00pm to 8:00pm, normally occupants arrive to home after work and have dinner during this period of times. Phase five (T5) is after 20:00pm until midnight. Based on five time phase, the results for different time of day with overall figures are presented in figure 4.21 and 4.22. Based on the window devices monitoring, the results showed that overall, the majority of occupants in both types of apartments used to open the window for ventilating and bring in fresh air during the morning time around 7:00am to 9:00am when they get up. This conclusion was also identified by other researcher, from findings of study conducted by Johnson and Long determined the probability of window opening and closing during time of the day. In general, the maximum of window openings occur in the morning. During cooking time of early afternoon, the number of open windows is relatively high (Johnson & Long, 2005).

Table 4.2 Summary of five main time phase

T1	0:00am-7:00am
T2	7:00am-9:00am
T3	9:00am-18:00pm
T4	18:00pm-20:00pm
T5	20:00pm-24:00am

Figure 4.21 Time of day effect on window opening for each each new apartments

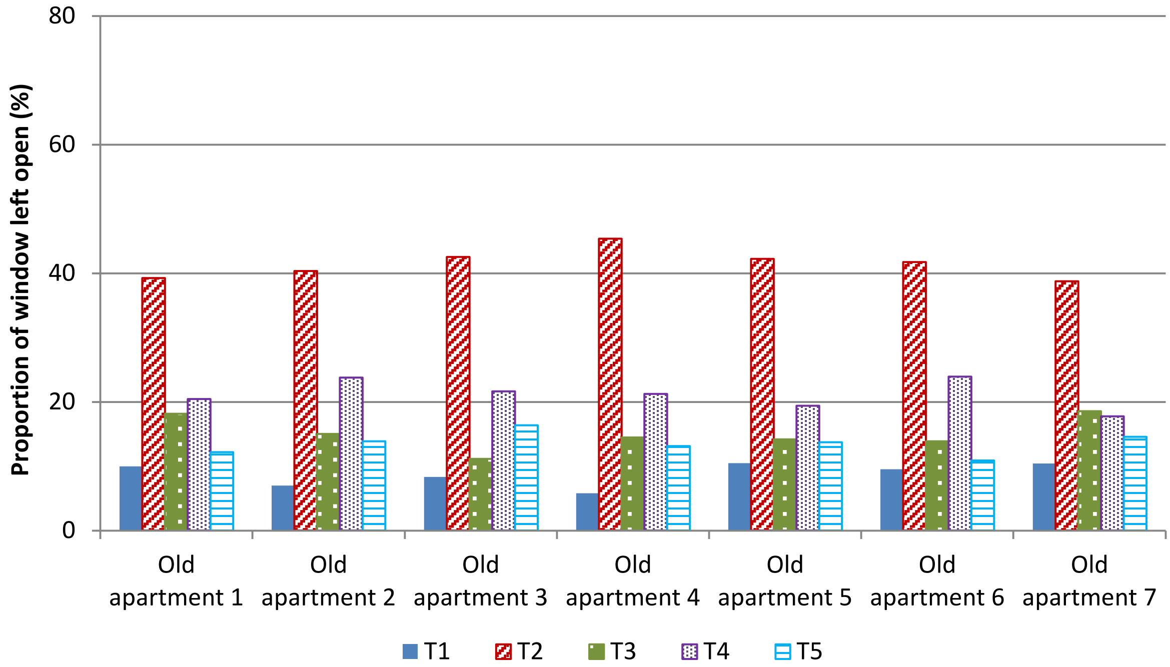


Figure 4.22 Time of day effect on window opening for each old apartments

From figure 4.21 and 4.22, the results were found that window opening behaviour difference due to different time of day in old and new apartments, respectively. The field measured data reflect that during the morning time, the windows in both old and new apartments were opened more compared with other phases of the overall monitoring time. This confirms the findings of Fabi et al suggested that the number of windows were most opened during morning time when people wake up (Fabi, et al., 2012b). Comparisons in figures, it is also need noted that the proportion of window opened are second highest during 18:00pm to 21:00pm, this conclusion was also identified by other researcher, in general, during cooking time of early afternoon, the number of open windows is relatively high (Johnson & Long, 2005).

4.3.1.5 Orientation of rooms effect on window operation

According to study of IEA Annex VIII project (Dubrul, 1988) found that the orientation of rooms is important to relate with window operation. The outdoor temperature were binned ranges from 10°C to 27°C, details ranges 10°C $\leq T_{out} < 15$°C, 15°C $\leq T_{out} < 20$°C, 20°C $\leq T_{out} < 25$°C, 25°C $\leq T_{out} < 27$°C. Therefore the relationship between the proportions of window opened and outdoor temperature according to window orientation in both old and new apartments can be identified. From Figure 4.23, it was observed that in general, south facing rooms were more likely to be opened than north facing rooms in old apartments. Figure 4.23 indicates outdoor temperature range from 25 to 27°C there are the significate different between south facing rooms and north facing rooms. This is most likely because of that if the room have more direct solar radiation during sunny day in winter, the more window opened by occupants.

The data observed from study for new apartments as shown in Figure 4.24. However, the differences between south facing rooms and north facing rooms, which are not appear obviously. Thus, in this study, the factor of window orientation can be treated as an influencing factor on the occupants' window behaviour. In particular, in old apartments with high indoor air temperature, the room in south face can be heat up quickly by direct solar gain, which means occupants opened window to decrease indoor thermal environment due to overheating. In this study, there were not found significate linked, it may be explained by the fact that the different type of building and lifestyle of occupants. There are some evidence of the orientation of room have effect on proportion of window opened in each new and old apartments individually. This is can be observed from Appendix F, there are slight variations between north facing and south facing rooms effect on window opening behaviour in new apartments. However, in each old apartments south facing room appear to have a significant impact on the window opened when outdoor temperature range from ≥ 25°C to < 27°C.

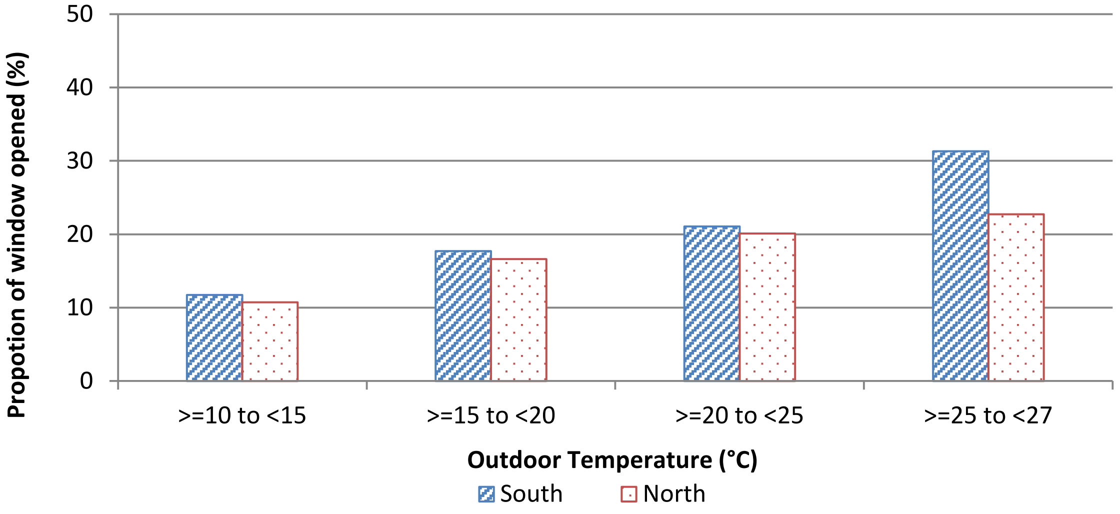


Figure 4.23 Proportion of window opened based on orientation of room for old apartments

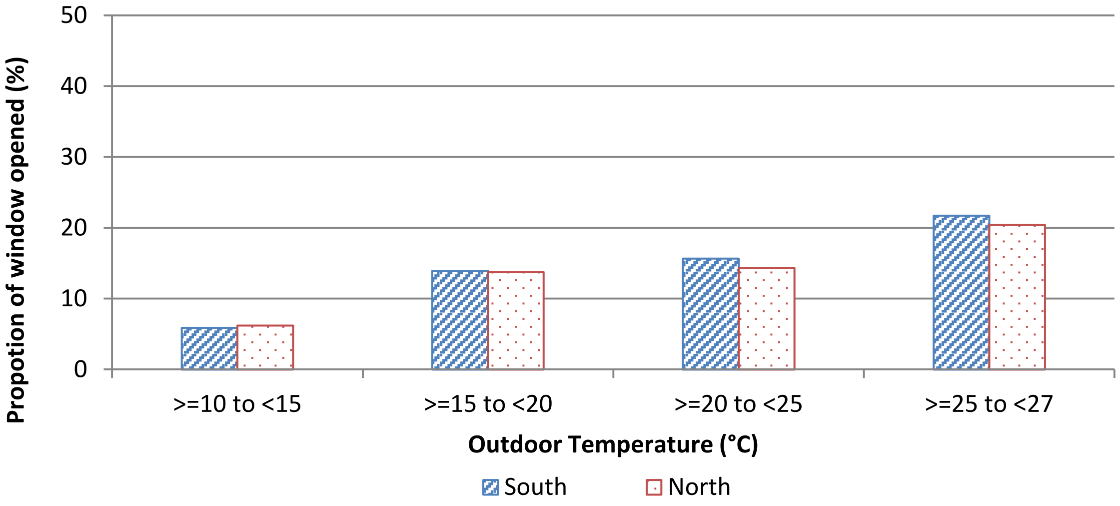


Figure 4.24 Proportion of window opened based on orientation of room for new apartments

4.3.1.6 Type of rooms effect on window opening

In overall, for all new apartments, the results reflect that windows in bedroom were opened for 28.9% of the monitoring time, while they were opened for 32.7% of the monitoring time in living room. In overall, for all old apartments, the windows in bedroom were opened for 43.8% of the monitoring time, while they were opened for 50.3% of the monitoring time in living room. Therefore, the effect of different type of rooms would be easier to identify from results.

Figure 4.25 shows the probability of window opened in living room and main bedroom for each new apartment. The results investigated that the slightly more percentages of window opened are in living room for new apartments. The percentage of window opened in living and bed room for overall monitoring time in each old apartment can be observed in Figure 4.26. It may reflect that the type of room have slightly more obvious effect on probability of window opening behaviour due to type of rooms in old apartments compared with that in new apartments. In addition, as previous study from Dubrul, it also found that in old apartments if occupants tend to open the windows to ventilate air in their bedrooms frequently and they also tend to open windows to ventilate air in their living room at high levels. However, this is not appearing significantly in new apartments (Dubrul, 1988).

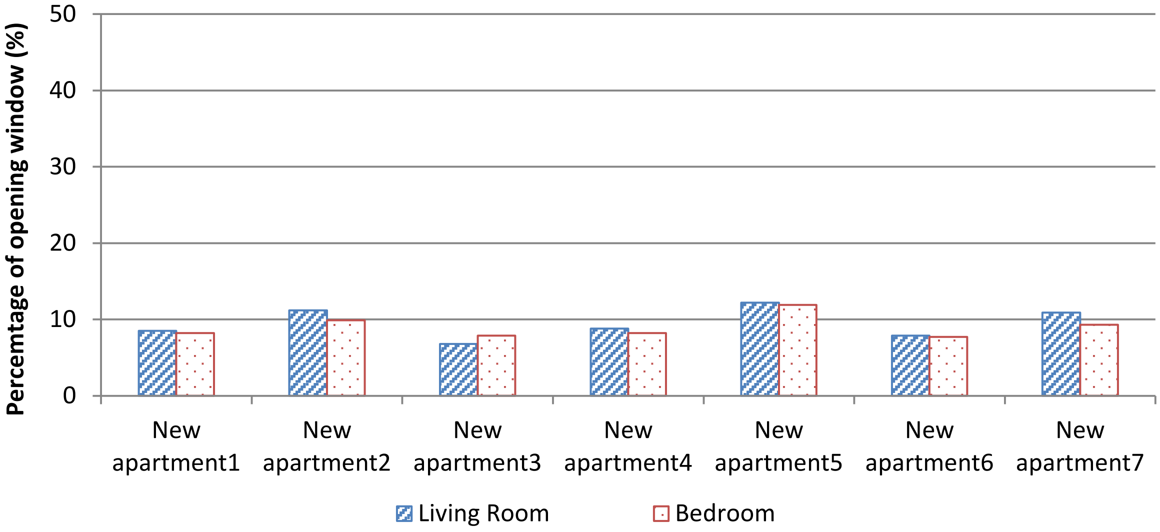


Figure 4.25 Type of room effect on window opening in new apartments

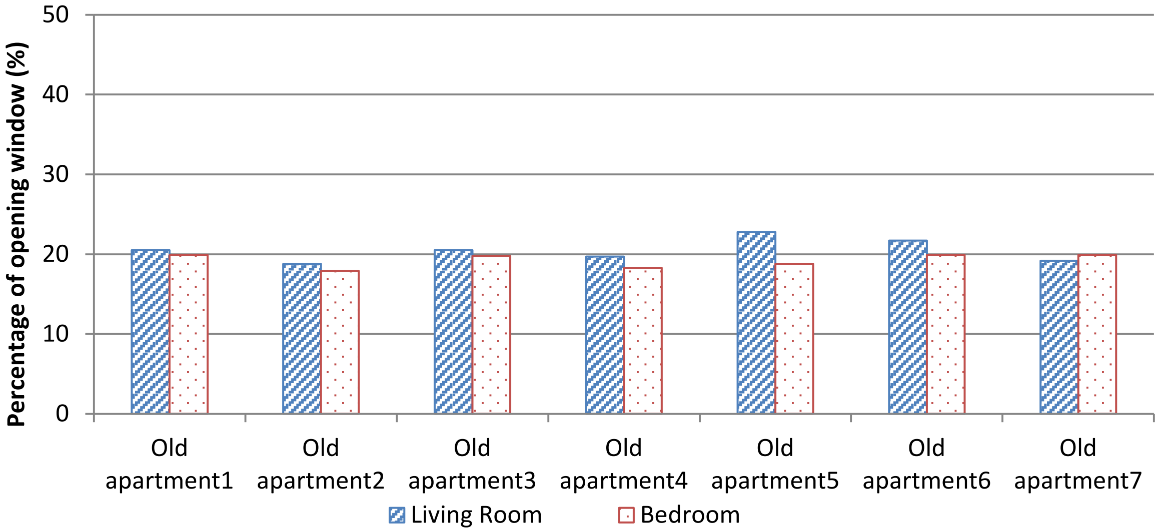


Figure 4.26 Type of room effect on window opening in new apartments

4.3.2 Results of reason for window opening

The occupant has their own habit to adjust their indoor thermal environment. It is hard to conclude that the connection between individuals and trend of window opening. The motivation of occupants for opening the window can be divided into domestic, environmental, social, health and hygiene, physiological and psychological (Dubrul, 1988). In order to identify the reason for household open the window, the questionnaires were conducted (Appendix A). In this study, the survey investigation reported by occupants reveal that the reason for occupants open their windows. It can be divided into three main parts:

1. Get fresh air
2. Remove moisture
3. Get lower indoor climate

In this study, the findings of main results from observation show that the most significant reasons for opening the window in old apartments, the surveys show that 65% of occupants agreed that they opened the window because high temperature and it was hot inside apartments. This is most reason for opening windows in old apartments. However, in new apartments only have 29% of occupants agreed that they opened the window because higher indoor climates, as shown in Figure 4.27.

This is may be explained by new heating control system and new heating payments were installed in new apartments. The correlations between window opening and the heating operation behaviour will be discussed further in section 4.4.

The investigation of questionnaires are presented in Appendix A, in questionnaires, the personal reasons of opening windows were investigated, occupants were asked to respond their one or more actions based on questionnaires. Therefore, the proportions do not add up to 100% in total. Also the figure shows the both new and old apartments were that the respondents wanted more fresh air, they are 57% and 50% respectively. It was particular in the morning time get fresh air bedroom is one of most reason for opening windows. In the new apartments survey 29% of the occupants want to remove moisture and in the old apartments survey 36% of the occupants want to remove moisture, respectively. It found that occupants in old apartments were more likely want to remove moisture. The reason related to this could be explained that different level of insulation, and previous study found that occupants living in single glazing dwellings open window more than occupants living in double glazing dwellings. This is partially related to occupants report removal of condensation on windows in single glazing dwellings (Dubrul, 1988).

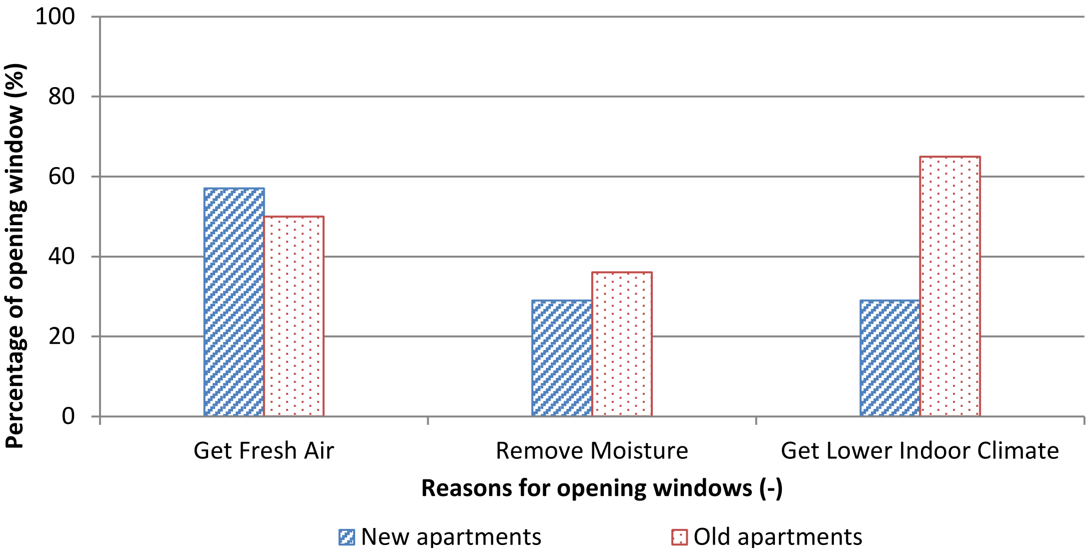


Figure 4.27 Agreement in the reasons for opening windows for new and old apartments

4.4 Heating behaviour in new apartments

4.4.1 Characteristics of adjustment of TRVs

Heating behaviour play an important role in adjusting indoor temperature. In new apartments, there are thermostatic radiators valves (TVRs) install in each radiator, the occupants can adjust it to achieve satisfied indoor environment. From the one week self-recording of heating behaviour and based on questionnaires, the occupants in new apartments adjust TRVs to change set-point behaviour can be concluded as three main patterns: first is only adjust TRVs once (i.e. apartment 5), second is adjust TRVs frequently during day (i.e. apartment 2, apartment 3 and apartment 6), third is TRV adjusting TRVs few times to keep long time on same set-point (i.e. apartment 1, apartment 4, apartment 7).

For first pattern of TRVs adjustments, in details, in apartment 2, 3 and 6, TRVs adjustments were very frequently compared with other apartments. Figure 4.28 shows an example of indoor temperature variation with TRVs adjustments in bedroom of apartment 6 during two sample days. It can be seen from figure, the air temperature fluctuate according to TRV adjusted by occupant during 6:40am to 8:35am when they wake up. At the time when they left to work after 8:35am, occupants turn down TRVs. However, combination of questionnaire and indoor climate measurement, it observed that TRVs set-point was turn up range from 1 to 4 at 7:34pm when they come back to home after work. When the outdoor temperature has dropped to 6.9°C the heating set-point range was increased.

Figure 4.29 shows an example of indoor temperature variation with TRVs adjustments in living room of apartment 6 during workdays. It can be seen from figure, the air temperature constant drop down during nigh time, between 12:00am to 5:31pm. Occupants prefer cool environment of living room and only turn on TRVs set-point between 5:50pm to 8:34pm. In addition, this figure shows that TRVs were turned down when they go to bed during night time in living room. The indoor temperature decrease constantly after TRVs was turned down to range 1.

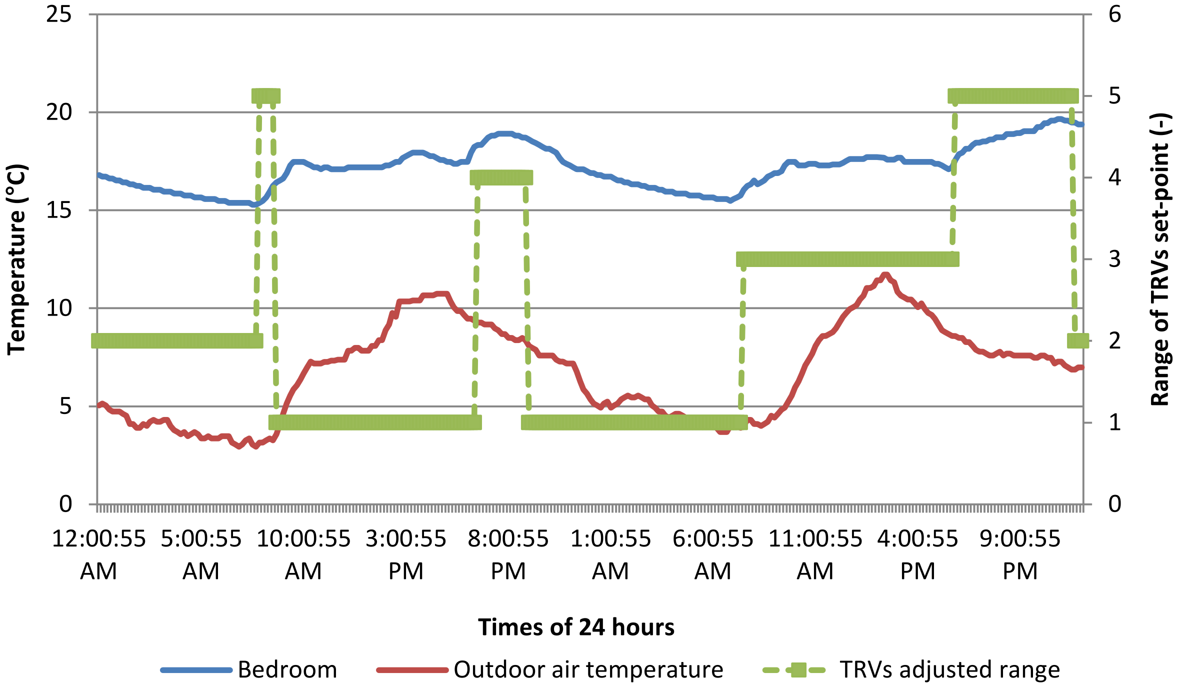


Figure 4.28 Two sample day plot of indoor and outdoor temperature with TRVs adjusted range in bedroom in apartment 6

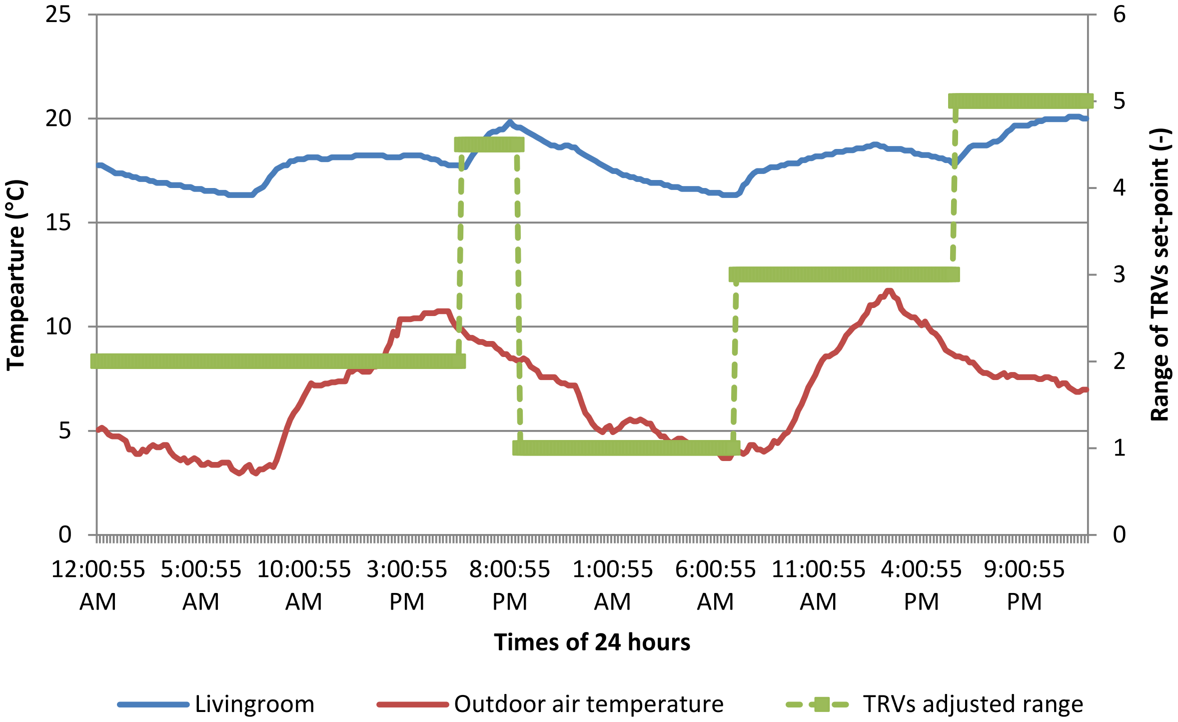


Figure 4.29 Two sample day plot of indoor and outdoor temperature with TRVs adjusted range in living room in apartment 6

From the comparison, it could be found that both the living room and the bedroom, TRVs were adjusted frequently in apartment 6. This confirms previous field experiments study (Xu, et al., 2009) carried out the results of occupants' behaviour in TRVs regulation in distract heating system residential buildings in Tianjin. They found that 28% of total occupants adjust TRVs frequently and even several times during a day. And occupants adjust TRVs according to occupants' schedule.

For second pattern of TRVs adjustments, in living room of apartment 5, TRVs adjustments were changed once and keep same set-point on range 4-5 during whole observed period. There have some evidence of TRVs were never adjusted and room were heated constantly. This is can be observed in Figure 4.30, the indoor air temperature keep constantly in bedroom in apartment 5 during two sample days. At the time the TRVs set-point were not changed. The air temperature is only drop slightly around 5:00pm. It may be related to window opened by occupants.

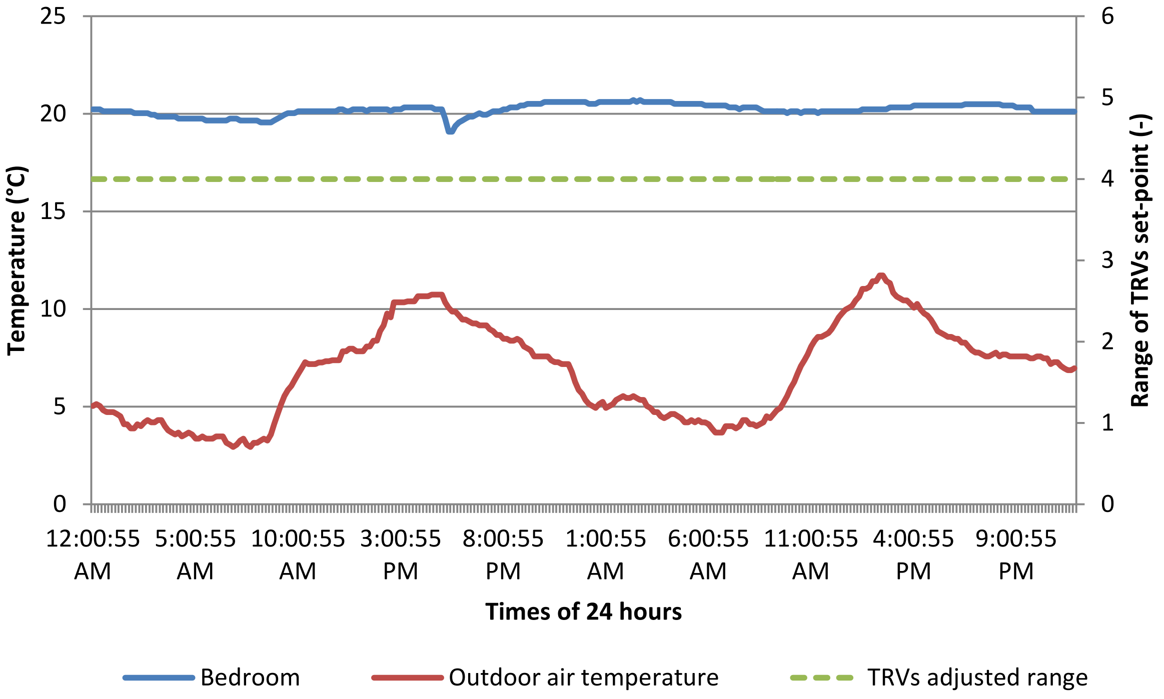


Figure 4.30 Two sample day plot of indoor and outdoor temperature with TRVs adjusted range in bedroom in apartment 5

Figure 4.31 show that the TRVs set-point were not changed and the indoor air temperatures were constantly in living room in apartment 5 during two sample days.

The air temperature is only deceased slightly from 7:10am to 7:40am. It could be related to window opened by occupants. As mentioned before, the detail information about correlation between TRVs set-point adjustment and occupant window opening behaviour will be further discussed in next section.

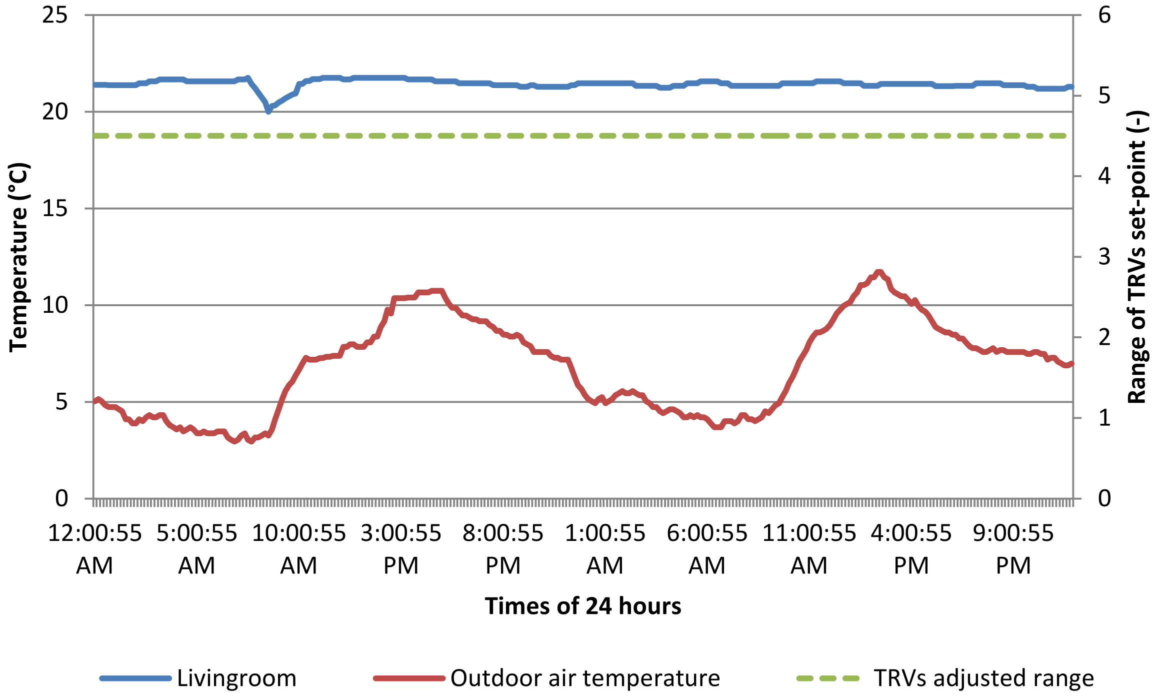


Figure 4.31 Two sample day plot of indoor and outdoor temperature with TRVs adjusted range in living room in apartment 5

For third pattern of TRVs adjustments, for instant, in both living room of apartment 2, occupants adjust TRVs once to keep long time on set-point 4-5, only turned down when outdoor temperature were relatively higher. In both living and bedroom of apartment 1, TRV were adjusted based on occupancy of occupants, it were not regular during workdays however it were adjusted few times in particular during weekend when occupants stay in home.

4.4.2 The potential factors effect on heating behaviour

4.4.2.1 Outdoor temperature

Both the questionnaire survey and the measurements showed that the outdoor temperature has an impact on the heating behaviour. Figure 4.14 presents the relationship between TRVs set-point adjustment as function of outdoor temperature and survey shows that the correlation between higher outdoor temperature and lower TRV set-point adjustment in new apartments. Furthermore, the investigation indicated that some occupants turned down the TRV set-point when opening window. The data demonstrates that the uses of TVRs of heating were significantly related to outdoor temperatures in this study. As previous study mentioned that the heating behaviour of domestic dwellings was related to the outdoor temperature. The heating behaviour influenced by factors of the outdoor temperature (Larsen, et al., 2010). This is confirms the findings of Andersen et al. It found that the use of thermostatic radiator valves set-point space heating have strong correlations with outdoor temperature (Andersen, et al., 2009).

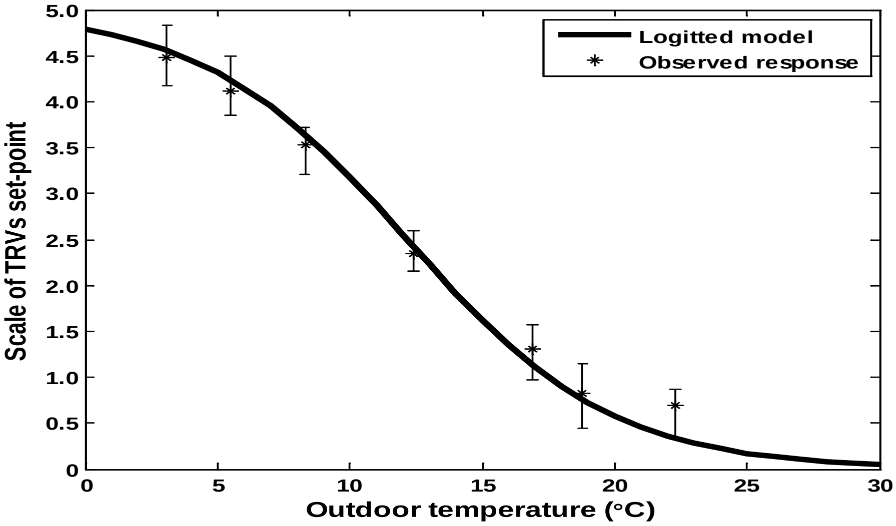


Figure 4.32 Logitted curve for TRVs set-point as a function of the outdoor temperature in new apartments

For this study, overall the mean indoor temperatures of both living and main bedroom in old apartments are higher than that in new apartments, it reveal that the occupants' behaviour of adjusting TRVs in new one and it also can be seen from questionnaire of adjusting TRVs by occupants. From another perspective, we might be able to explain this significant phenomenon by looking at the different heating system and heat billing systems, hence the occupants can adjust the TRVs in radiators if the room is overheated or they prefer to use lower heating energy for cost of heat billing.

4.4.2.2 Occupants of personal factors

Based on investigation of individual background questionnaire, Table 3.6 in section 3.4.4 describes that individual social background in each apartment. From the table, the education level of each household are presented. The education level of occupants in apartment 3 and apartment 6 are relatively higher than occupants in other apartments. From the one week self-recording of heating behaviour and based on questionnaires, the occupants in apartments 3 and 6 adjust TRVs frequently to change set-point. This is may reflect that the correlation between occupants have higher education level, higher requirements they have. The data from previous study supports this finding. The education level was a factor influencing use of heating has been confirmed in previous study (Guerra-Santin & Itard, 2010).

4.4.2.3 Dwelling age and type of rooms:

In our study, the new case study building were built within five years and old one were built at late 1990s, the insulation level of each building are significant different. Furthermore, for the winter heating period, occupants in newer apartments achieve their satisfied thermal environment via using TRVs control system. Therefore it is assumed that the different heating behaviour could be due to different building ages. This is confirms the finding of correlations between ages of dwellings and use of energy on heating (Hunt & Gidman, 1982).

The relationship between type of room and adjustment mode of TRVs have been identified in this study. Figure 4.33 shows the probability of TRVs adjustment in living room and main bedroom for each new apartment. The results investigated that in apartment 6 presents the highest frequency of TRVs adjustment of overall monitoring week. In addition, occupants in apartment 3 also prefer to adjust TRVs in both bedroom and living room of overall monitoring week. It may reflect that the occupants tend to adjust TRVs in their bedroom and they also tend to adjust similar level in the living room. However generally in all apartments, the different type of rooms influence TRVs adjustments is very weak.

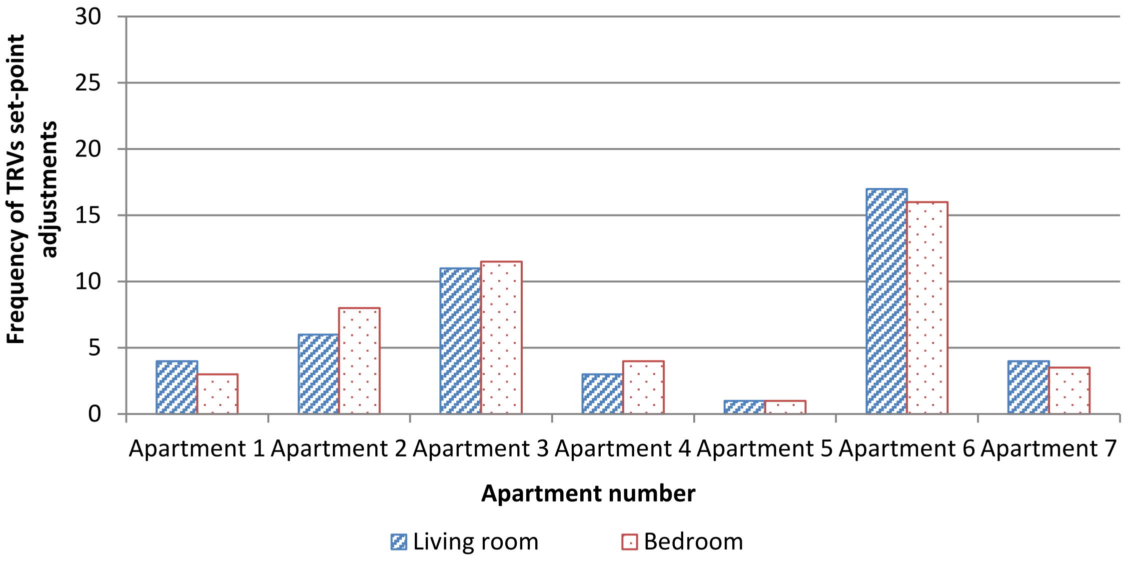


Figure 4.33 The frequency of TRVs set-point adjustment in both living and bedrooms in all new apartments

4.4.2.4 Energy price

Occupants in new apartments open their window much less than those in old ones. This is may be due to the fact that home with different heating bills systems. Occupants in new building can adjust TVRs in order to achieve their satisfied indoor thermal environment and they can adjust TRVs set-point in order to get less heat. Therefore, in this study the heating payment bill influencing on occupants' heating use and also the use of windows. In old apartments, occupants only pay once for heating bill during whole heating season. It is depended on floor areas in each apartment. Therefore, occupants do not need pay more attention to heating payment bill and heating energy consumption. The correlation between energy consumption for space heating and energy price has been confirmed by empirical study, increase in the average price of energy used in the chosen heating technology is estimated to reduce energy consumption (Nesbakken, 2001).

4.4.3 The correlation between heating behaviour and window opening

The questionnaires and measurements of TRVs set-point adjustment showed that the outdoor temperature have an influence on occupants' heating behaviour. And other potential parameters were analysed in above sections, such as type of rooms, dwelling age and energy price. Dwelling age and energy price were found to have influence on occupants' heating behaviour. In our study, according to investigation the occupants keep TRVs set-point at a lower setting level, occupant opened window less than that the occupants keep TRVs set-point at higher setting level in other apartments. In addition, based on all results of questionnaires and measurement of operation of window opening, it found a negative correlation between TRVs setting and window behaviour. Few previous studies have confirmed that a negative correlation between thermostat set-points and window opening behaviour (Dubrul, 1988; Andersen, 2009).

4.5 Energy consumption

During the survey period, the energy consumption of seven new apartments and seven old apartments have been monitored and compared in this section. As mentioned in section 3.3, the heat meters were equipped into all household in new apartments. The heating energy consumption was achieved by in-situ measurement of the recording by the residential heat meter in each apartment. However, the heating energy used in each old apartment was measured manually. Based on the measured parameters, the heat consumed by each apartment can be calculated based on the theory of heat meter in new apartments. The results presented in Figure 4.34 indicated that the energy consumption in new and old apartments during whole experimental periods. Furthermore, Table 4.3 gives the energy consumption for new and old apartment based on areas in total. The results show that the new apartments total consumed 5863.2 kWh heating energy during the survey period and that in the old apartments total consumed 11070.7 kWh heating energy, leading to an energy saving of 45%. Overall from real-time measurement of different end-use heating energy consumption, it reflects the energy uses in old apartments are higher than that in new ones. Therefore, it is important to assess the correlation between potential factors affecting on heating energy consumption, next section 4.5.1 and 4.5.2 summarise each potential factors.

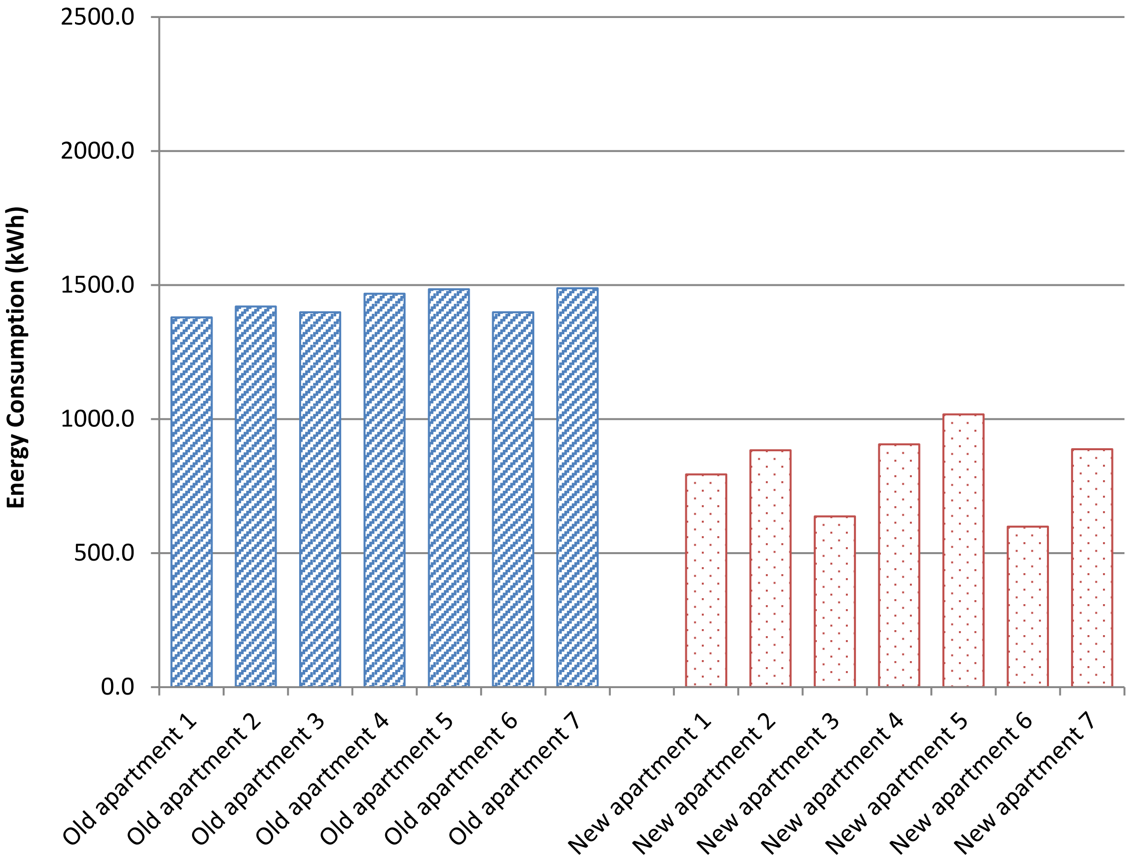


Figure 4.34 Comparison of energy consumption in new and old apartments

Table 4.3 Energy consumption of new and old apartments based on aeras

	Energy used in New apartments	Energy used in Old apartments
1	8.48kWh/m^2/month	20.42 kWh/m^2/month
2	8.49 kWh/m^2/month	20.80 kWh/m^2/month
3	8.22 kWh/m^2/month	18.31 kWh/m^2/month
4	11.38 kWh/m^2/month	17.27 kWh/m^2/month
5	11.75 kWh/m^2/month	21.46 kWh/m^2/month
6	7.57 kWh/m^2/month	20.09 kWh/m^2/month
7	11.85 kWh/m^2/month	15.76 kWh/m^2/month

4.5.1 Analyses on influence factors of heating energy consumption

In this analysis, previous studies indicate that residential energy consumption is not only influenced by building characteristics but also influenced by household characteristics, occupant behaviour, and efficiency of the service system (Haas, et al., 1998). To identify how each potential factors impact on heating energy consumption in this study. The insulation level, occupant behaviour and household characteristics were analysed. Different levels of insulation have significant impact on energy use, in other words, better insulated dwellings use much lower energy than that in less insulated dwellings. Insulation level can be treated as an important parameter in demand of heating in dwellings (Santin, et al., 2009; Schuler, et al., 2000; Haas, et al., 1998). Recently, in Chinese residential buildings, the building standards mandatory require improving the insulation in new residential buildings. Experience tells us and previous study confirms that well-insulated building not only can improve occupants' environmental comfort, but also reduce heating energy consumption. In this study, as section 3.5 descript the insulation level in new apartments have much better insulation than the old ones based on the building design standards (JGJ26-2010, 2010; GB50176-93, 1993). This is one of reason for new apartments employ with new standards consumed less energy. Regarding the window structure, old apartments used single glazing and new apartments used double glazing. Double glazing used air inside two glasses lead to smaller heat transfer coefficient and it helps to save energy. Therefore, it may be reflect that the better insulated new residential building lead to more energy saving and save money (Liu & Liu, 2011). Conclusion of finding has been confirmed by previous studies that the lower energy consumption in newer apartments due to new building regulations, In addition, higher energy use of space heating in older apartments, the reason for this may be due to better insulation in newer apartments than in older apartments (Leth-Petersen & Togeby, 2001; Nesbakken, 2001).

It is worthy to note that occupant behaviour interaction with the thermal environmental. The actual usage of building changes on a daily basis. Therefore, it is worth to take into account the importance of occupant behaviour in residential buildings, shows following below (Maile, et al., 2007). According to Xu et al (2009) investigated that the central heating system with TRVs adjusted by occupants in Chinese new residential buildings together with new heating payment. It was concluded that momentous difference in the frequency of occupant adjusted the TRVs set-point result in energy saving compared with old traditional heating payment. Essentially, by the literature, this is one of reason for new apartments consumed energy lower than old ones and this confirms in our study.

4.5.2 Households variables and energy consumption

Previous research has shown that the household income is one of the most significant drivers of energy use for space heating. Each household income was collected during questionnaire interview. It is note that household income is likely to have impact on heating control system usage in new apartments. In apartment 5 the household income is relatively higher than household in other apartments, and this apartment consumed highest heating energy use. Consequently, it revealed that higher household income connect to higher energy consumption in apartment 5. It is need to mention that the floor area likely to have indirect important impact on energy use related to income. Because higher income families live in bigger apartments that then in turn impacts on energy consumption (Chen, et al., 2013). This is also confirms of findings from previous study revealed that the mean of income increased by 1% lead to the mean of energy consumption increased by 0.04% for space heating (Sardianou, 2008). However, in apartment 2, household income also relatively higher than others, there are negative relations between incomes and heating energy consumption was found.

Education level was expected to affect the use of heating related to final energy consumption, it is worth noticing that the households in apartments 3 and 6 adjust TRVs frequently to change set-point related to higher education level so that higher requirements they have. Therefore, they may have higher awareness to reduce energy consumption via adjust TRVs set-point (Guerra-Santin & Itard, 2010).

In our study, a substantial correlation between age of occupants and residential energy consumption have been demonstrated, it was found that the older occupants in apartment 5 contribute to higher energy consumption compared with younger occupants in other apartments. What follows is a discussion on the potential reasons for this phenomenon by different education level and lifestyles between older and younger in China.

4.6 Heat loss comparison in new and old apartments

4.6.1 Fabric heat loss in new and old apartments

In order to determine the difference heat loss between old and new apartments influence on energy consumption. The theoretical of heat loss need to be worked out by using calculation methods. Indeed, in order to maintain comfort in winter, the heat lost must be replaced by a heating system and insulation level provide an effective resistance to the flow of heat lead to decrease the energy needed for heating. While this saves on running cost for the building and helps the environment by reducing dependence on fossil fuels. It is obvious to note that it is hard to achieve a near zero U-value for all parts of a building fabric via physically or economically methods. However, it is important to note that in order to reduce heat loss from buildings, the simplest way to reduce fabric heat loss from building is to improve insulation level. The thermal transmittance (U-value) of the building fabric is the most significant factor that influences the heat loss from building and also lower U-value can lead to lower heat loss (Intelligent energy-Europe, 2011; CIBSE, 1999). In our study, U-value of new and old apartments was given above, and it indicates much better the U-value in new apartments than that in old apartments. The indoor and outdoor temperatures were test by using data loggers, the temperature difference between indoor and outdoor can be worked out. As mentioned in section 3.5.4, the details of calculated dimensions of areas in all new and old apartments were list in table 3.11. To calculate the total fabric heat loss from all apartments by using appropriate equations involve calculate heat loss through the blockwork firstly, calculate the heat loss through and windows and doors secondly, however, it is normal to ignore the door without glazing and add into wall area in most calculations and finally calculate heat loss through floor and roof. Therefore, table 4.4 shows total fabric heat loss from all apartments calculated together with the details of dimensions for the area calculation. Table 4.4 shows that the heat loss through fabric in old apartments is much higher than that in new apartments. The results reflected that better insulation level lead to lower heat loss and therefore influence energy use and indoor temperature in this study. Lower U-values in new apartments will results in heat loss through fabric decreases compared with that in old apartments. The principle of building physics show that during cold conditions heat loss through the fabric increase and high indoor temperatures will lead to greater heat loss and more energy use (Kane, 2013).

Table 4.4 Total fabric heat loss for new and old apartments

	Total Qf in old apartments (Watts)	Total Qf in new apartments (Watts)
Apartment 1	2164.70	805.34
Apartment 2	2149.89	939.34
Apartment 3	2262.57	865.41
Apartment 4	2227.16	948.63
Apartment 5	2024.88	982.03
Apartment 6	2297.99	836.80
Apartment 7	2333.40	966.63

***Qf** *is the value of fabric heat loss of buildings*

4.6.2 Ventilation heat loss in new and old apartments

Ventilation heat loss in building brings outside cold air replaces the warm inside air. It is important to note that in order to reduce heat loss from buildings, lower possible ventilation rate lead to lower heat loss. Indeed it is necessary to comply with minimum ventilation rates set by government regulations have minimum amount of air change via ventilating to provide adequate supply of fresh air and high indoor air quality (Intelligent energy-Europe, 2011). In our study, as mentioned previously, the U-value of new and old apartments was given, the difference between indoor and outdoor temperature were worked out. Infiltration rate (ac/h) was determining with Chinese building standards provide a value of 0.6 ach of air change per hour. Volumes of rooms in the new and old apartments were calculated previously given in table 3.11. Johnson suggested that geometric mean to change from 0.76h-1 for no openings to 1.51 h- 1 for one opening, 2.30 h- 1 for two openings and 2.75h -1 for three or more openings (JOHNSON, et al., 2004). Calculate the total heat loss from all new and old apartments shown in table 4.5. It can been seen from below calculations that heat loss through fabric are higher than heat loss through ventilations in both new and old apartments. However, the calculations of assumption of air change rate for both new and old apartments offer a value of 0.6 ach based on Chinese building standards. Obviously, in this study, the overall field measured data reflect that the windows in all old apartments were opened for 54% of the monitoring time, while they were opened only for 29% of the monitoring time in all new apartments. It is therefore important to establish accurate value for air change rate in two different types of apartments. It was also found in Table 4.5, the heat loss through fabric for old apartments are significant different from new ones. However the heat loss from ventilation for old apartment is slightly different from new one. It is therefore in order to ensure defined air change rate in the different type of apartments, the air change values can be corrected sufficiently under reasonable conditions in practice assumed as 0.76, 1.51, 2.30 ac/h.

Table 4.5 Total heat loss from all new and old apartments

	Old apartments			New apartments		
	∑Qf (Watts)	∑Qv (Watts)	∑Qtotal (Watts)	∑Qf (Watts)	∑Qv (Watts)	∑Qtotal (Watts)
Apartment 1	2164.70	232.10	2396.80	805.34	228.36	1033.71
Apartment 2	2149.89	231.24	2381.14	939.34	226.18	1165.53
Apartment 3	2262.57	242.62	2505.20	865.41	196.01	1061.43
Apartment 4	2227.16	238.76	2465.93	948.63	222.50	1171.14
Apartment 5	2024.88	249.12	2255.01	982.03	234.73	1216.76
Apartment 6	2297.99	246.45	2544.44	836.80	194.57	1031.37
Apartment 7	2333.40	283.29	2616.70	966.63	205.78	1172.42

****Qf** is the value of fabric heat loss of building; **Qv** is the value of ventilation heat loss of building*

The total ventilation heat loss in old apartments calculated with air change rate at 0.6ac/h in new and old apartments are also presented in table 4.6 and different air change rate have significant effect on total ventilation heat loss in different type of apartments. The air change rate at 2.3ac/h in ventilation heat loss calculation obviously differs from the air change rate at 0.6ac/h in ventilation heat loss calculation. In old apartments, the higher air change rate at 1.51ac/h resulted in ventilation heat loss that was increased by 61.1% averagely than air change rate at 0.6ac/h. In new apartments, the higher air change rate at 0.76ac/h resulted in ventilation heat loss that was increased by 21.1% averagely than air change rate at 0.6ac/h. It is therefore as shown in table 4.6, the higher ventilation heat loss due to increase of air change rate in both new and old apartments.

Table 4.6 Comparison of corrected ac/h in new and old apartments

Old apartments	ac/h at 0.6 (Qv in Watts)	ac/h at 0.76 (increased %)	ac/h at 1.51 (increased %)	ac/h at 2.3 (increased %)
1	232.10	315.99 (22.5%)	638.62 (62.5%)	914.72 (71.5%)
2	231.24	314.91 (22.5%)	626.47 (62.1%)	921.45 (72.9%)
3	242.62	307.32 (21.2%)	610.60 (60.3%)	930.06 (73.9%)
4	238.76	302.43 (21.2%)	600.89 (60.3%)	915.27 (73.9%)
5	249.12	308.16 (20.2%)	653.32 (61.9%)	960.48 (74.1%)
6	246.45	312.17 (21.2%)	620.23 (60.3%)	944.73 (73.9%)
7	283.29	358.83 (21.2%)	682.95 (60.3%)	985.95 (71.3%)

New apartments	ac/h at 0.6 (Qv in Watts)	ac/h at 0.76 (increased %)	ac/h at 1.51 (increased %)	ac/h at 2.3 (increased %)
1	228.36	268.28 (20.2%)	493.30 (60.7%)	791.39 (72.6%)
2	226.18	286.49 (21.1%)	569.22 (60.3%)	867.03 (71.5%)
3	196.01	260.65 (21.1%)	517.88 (62.2%)	788.83 (71.5%)
4	222.50	281.83 (21.1%)	559.96 (60.3%)	852.92 (73.1%)
5	234.73	297.32 (21.1%)	590.74 (60.3%)	899.80 (72.5%)
6	194.57	246.45 (21.1%)	529.66 (60.3%)	745.85 (71.5%)
7	205.78	289.26 (21.1%)	524.71 (62.2%)	875.39 (71.3%)

In original, the calculations of air change rate of new and old apartments were assumed as 0.6ac/h. However, as mentioned above, the windows in all old apartments were opened longer than that in all new apartments of the monitoring time. In addition, it was found that previously the higher ventilation heat loss due to increase of air change rate in both new and old apartments. As a consequence, the reasonable air change rate corrected to 0.76ac/h in new apartments for calculation and corrected to 1.51ac/h in old apartments for calculation.

Table 4.7 lists sum of heat loss in old apartments compared to sum of heat loss in new apartments. The air change rate was explored using 1.51 in old apartments and will results in higher total heat loss which increased by 14.1% compared with original total heat loss. Meanwhile, the air change rate was explored using 0.76 in new apartments and result in higher total heat loss which increased by 5.1% compared with original total heat loss. As a consequence, the useful comparisons of calculated total heat loss in new and old apartments were presented above. After corrected the appropriate air change values calculation in two types of apartments, the reasonable air change rate can be assumed as 0.76ac/h in new apartments for simulation models and 1.51ach/h in old apartments for simulation in models. A summary of the information is presented in further section 5.2.2.

Table 4.7 Reasonable correction of ac/h and total heat loss in new and old apartments

	Qf (Watts)	**Qv (Watts) ac/h at 1.51**	**$\sum Q_{total}$ (Watts)**	**Q_{total} (Watts) ac/h at 0.6(default assumed))**	**Increased (%)**
Old apartment 1	2164.70	618.62	2783.32	2496.80	0.141
Old apartment 2	2149.89	626.47	2776.36	2481.14	0.145
Old apartment 3	2262.57	610.60	2873.18	2505.20	0.146
Old apartment 4	2227.16	600.89	2828.06	2465.93	0.146
Old apartment 5	2024.88	653.32	2678.20	2455.01	0.147
Old apartment 6	2297.99	620.23	2918.23	2544.44	0.146
Old apartment 7	2333.40	712.95	3046.36	2516.70	0.146

	Qf (Watts)	**Qv (Watts) ac/h at 0.76**	**$\sum Q_{total}$ (Watts)**	**Q_{total} (Watts) ac/h at 0.6(default assumed)**	**Increased (%)**
New apartment 1	805.34	248.28	1053.63	1133.71	0.049
New apartment 2	939.34	286.49	1225.84	1165.53	0.051
New apartment 3	865.41	260.65	1126.07	1061.43	0.055
New apartment 4	948.63	281.83	1230.47	1171.14	0.050
New apartment 5	982.03	297.32	1279.35	1216.76	0.051
New apartment 6	836.80	246.45	1083.26	1031.37	0.051
New apartment 7	966.63	289.26	1255.90	1172.42	0.054

4.7 Comparison of heating cost in new and old apartments

The new building standard is not only aim to reduce the existing residential buildings energy consumption and to improve indoor thermal comfort, but also to decrease heating cost. The centralization heating is commonly used in residential buildings in

China and it comprised uncontrolled heating system with payment based on floor areas of occupants' apartments. Heating consume tremendous energy wastes in residential buildings during winter. New building standard installed and payments of heating are relied on metered consumption in each apartment and provide incentives to occupants to use heat efficiently and to control their heat consumption during heating season in winter.

Take account of whole heating season is from November 15th to March 15th 2014 thus total heating season is 115 days. In old apartments, heat payment bills are calculated based on prices per square meter of heated areas. Heat tariff is set by local government in each province, which keep stable for many years. During the winter, for the old apartments in that community, the heating price is 5.3RMB/m^2 (XASRLGS, 2012). Occupants were asked for paying heating bill at the beginning of heating season.

In new apartments heat metering bill include two main portions, one portion is based on floor areas and another portion is based on measurement of heat meter in each household according to actual heating use. The reform of heating payments bill system is aim to improve occupants' awareness of more efficiency on heating energy usage. The reform of heat price with measurement of heat meter is 0.16RMB/kWh. The reforms of tariffs were descried in section 2.4.2 (XASRLGS, 2012). Thus total energy price can be calculated as following equations:

$$\boldsymbol{f_b} = (\mathbf{1.74} \times \boldsymbol{f_h} \times \mathbf{30}\%) \times \boldsymbol{A_{floor}} \times \mathbf{4} \quad \textbf{(12)}$$

Where

f_b is basic energy price,

f_h is heating price per meter square per month,

A_{floor} is floor areas of each apartment

$$\boldsymbol{f_m} = \boldsymbol{f_Q} \times \boldsymbol{Q_t} \times \mathbf{70}\% \quad \textbf{(13)}$$

Where

f_m is actual metered energy use

f_Q is heating price per kWh

Q_t is total heating energy use metered by heat meter devices

Thus, finally total energy price of new apartment can be calculated as:

$$f_{total} = f_b + f_m$$

Table 4.8 shows that each household of annual heating cost in new and old apartments are compared. The implications of heating bill reform were assessed, as a consequence, the reform of heating bill system have significant effect on economic and energy saving. According to table 6.1, the mean heating energy cost in old apartments is 2160.2RMB and the mean heating energy cost in new apartments is 1053.8RMB which is respectively 1106.4RMB less than the cost in old apartments.

Table 4.8 Comparison of total heating cost paid by each household in new and old apartments

Apartment No	Old apartments Total heating payment (RMB/per household)	New apartments Total heating payment (RMB/per household)
1	1983.8	952.1
2	1983.8	1230.3
3	2204.8	986.9
4	2204.8	1005.8
5	1983.8	1245.3
6	2204.8	993.9
7	2555.8	962.6

4.8 Summary

This chapter has analysed the results of experimental data from measurements in both new and old apartments. Further to this, all potential factors such as indoor thermal environment, occupant behaviour and thermal comfort related to heating energy consumption of new and old apartments were compared respectively.

- According to the results, the indoor temperature differences between old and new apartments were obvious. The observations indicate that the trend of indoor temperature is generally changed with outdoor temperature in both new and old apartments. The indoor temperatures in old apartments are generally higher than that in new apartments.

- The overall field measured data reflect that the windows in all old apartments were opened for 54% of the monitoring time, while they were opened only for 29% of the monitoring time in all new apartments. Overall, observed results reflect that indoor temperature increased from 15 to 20°C, the more windows opened obviously by occupants in old apartments. For all old apartments, the proportion of windows opening strongly related to indoor temperature in both living room and main bedroom. However, there was a slight increase in the probability as the indoor temperature increased in new apartments.
- From one week self-recording of heating behaviour and questionnaires. The data suggests that the use of TVRs by occupants for heating was related to outdoor temperatures in this study. Additionally, the finding show that age of dwellings, education level of occupants, energy price can be factors that impact the use of energy for heating.
- The results show that the new apartments consumed lower heating energy than the old apartments during the survey period and lead to an energy saving of 45%. The mean heating energy cost in new apartments is respectively 1106.4RMB less than the cost in old apartments.
- The difference heat loss between old and new apartments influence on energy consumption were determined. As a consequence, the reasonable air change rate corrected to 0.76ac/h in new apartments for calculation and corrected to 1.51ac/h in old apartments for calculation.

Chapter 5

SIMULATED MODEL: VALIDATION AND SIMULATION RESULTS

5 Model validation and simulation results

5.1 Introduction

This chapter presents the simulation results related to relevant academic research area of this thesis. It divided into two main categories, one is validation assessment, measured data of weather files, occupancy patterns and energy supplied by heating system were used to simulation for calibrating models. Another is the comparison of simulated and measured results, how each factor impact on energy consumption and the further assessment and results were discussed.

5.2 Validation of final energy consumption in new and old apartments

The aim of model validation is to make sure the simulated model operated in a qualitatively realistic way compared with actual performance of building (Hilliaho, et al., 2016). Figure 5.1 shows the comparison analysis of real measured total energy consumption in new apartments and old apartments, also shows the predicted total energy consumption in old and new model simulation blocks. The measured results show that in the new apartments total consumed 5863.2kWh heating energy during the survey period and this in the old apartments total consumed 11070.7kWh heating energy, leading to an energy saving of 45%. Moreover the model simulation results indicated that in the new model blocks total consumed 4848.2kWh heating energy during the survey period and in the old model blocks total consumed 10036.1kWh heating energy, leading to an energy saving of 48.6%.

Energy modelling regarded as a useful design tool have been identified in two academic buildings located in Gainesville by Reeves et al. In their study, results show that energy simulations obtained by three building energy modelling were compared to the measured data in terms of heating, cooling, and overall energy usage. It was found that to assess the accuracy of simulation tool, the percentage differences for energy use between simulation and measurements were analysed and calculated as following equation:

Percentage Difference = [(Simulated Results – Measured Results) / Measured Results] x 100%.

According to previous study, the acceptable percentage difference between simulation results and measured results is maximum 15% (Maamari, et al., 2006). Thus, the absolute values of the percentage difference were equal to or less than 15% can be regarded as acceptable accurate results (Reeves, et al., 2012). In our study, the measured heating energy consumption in old apartments is 11070.7kWh and the simulated data is 10036.1kWh which is respectively 1034.6kWh lower than the measured ones. It reveals the differences between measured and simulated data in old apartments were within 9% range, which means a good agreement between the measurement and the simulation results in old apartments. However, there are an obvious difference between the measurement and the simulation results in new apartments. The discrepancy between simulation and measured results were not significant (within 15% different range). Figure 5.1 shows similar measured energy consumption and simulated energy consumption. It is hard to expect a perfect fit when comparing simulation results with measurements in a real building. The reason for explanations is too many uncertain parameters and unknown variables because they are not monitored. Furthermore the real system sensors are not very accurate (Lain, et al., 2005). This is can be related to the occupants' heating behaviour in new apartments, occupants can adjust the TRVs of heating in order to satisfy their needs for indoor environment. Furthermore, the limitation of simulation is not able to predict the real occupants' heating behaviour in new model block. Additionally, in new model blocks simulation, the input of TRV heating set-point replaced with measured mean air temperature. Thus, there are reliable discrepancies between simulation results and the actual measured results of real new apartments. However, occupied dwellings are observed to consume more energy than the models predict at design stage (Sutton, et al., 2012). As a consequence, there have good agreement between the simulation results and measurement results for new and old apartments.

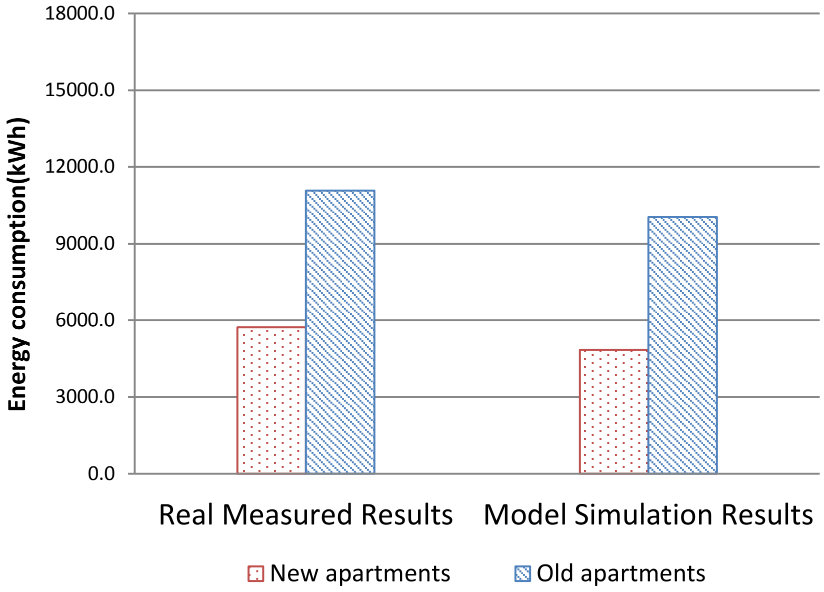


Figure 5.1 Comparisons of total energy consumption in measured and simulation for old and new buildings

5.2.1 Comparison results of real measured and simulate energy consumption in each new and old apartments

As previous mentioned the dynamic simulation results were agreement with the findings of the field measured data. Figure 5.2 illustrates actual measured data and simulation results for each old apartment. It can be observed that for all apartments the measured heating energy consumption and the simulated data which are respectively lower than the measured ones.

In old apartment 1, the measured heating energy consumption is 1558.2kWh and the simulated data is 1378.9kWh which is respectively 179.3kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 12% range, which means acceptable percentage different. In old apartment 2, the measured heating energy consumption is 1586.7kWh and the simulated data is 1419.9kWh which is respectively 166.8kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 11% range, which means acceptable percentage different. In old apartment 3, the measured heating energy consumption is 1553.2kWh and the simulated data is 1398.5kWh which is respectively 154.5kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 10% range, which means acceptable percentage different. In old apartment 4, the measured heating energy consumption is 1559.9kWh and the simulated data is 1468.9kWh which is respectively 91.6kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 6% range, which means acceptable percentage different. In old apartment 5, the measured heating energy consumption is 1598.8kWh and the simulated data is 1483.9kWh which is respectively 114.9kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 7% range, which means acceptable percentage different. In old apartment 6, the measured heating energy consumption is 1565.2kWh and the simulated data is 1428.9kWh which is respectively 136.2kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 9% range, which means acceptable percentage different. In old apartment 7, the measured heating energy consumption is 1548.2kWh and the simulated data is 1387.6kWh which is respectively 161.3kWh lower than the measured ones. It reveals the difference between measured and simulated data was within 10% range, which means acceptable percentage different.

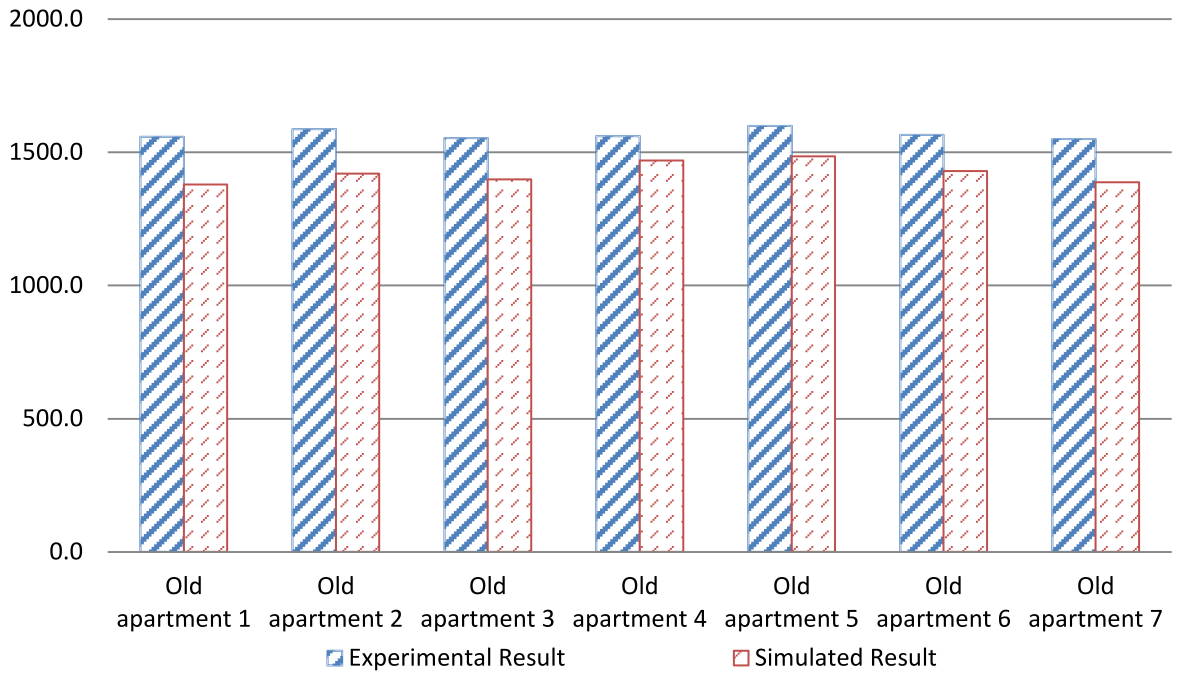


Figure 5.2 Actual and predict of energy consumption in old apartments

Figure 5.3 illustrates measured heating energy consumption and the simulated data in each new apartment and it indicate that overall simulated data are respectively lower than the measured ones. In new apartment 1, the measured heating energy consumption is 793.5kWh and the simulated data is 684.8kWh which is respectively 108.7kWh lower than the measured ones. It reveals the percentage difference between measured and simulated data was 14%, which means within acceptable percentage different. In new apartment 2, the measured heating energy consumption is 883.6kWh and the simulated data is 763.9kWh which is respectively 119.6kWh lower than the measured ones. It reflects that the percentage difference between measured and simulated data was 14%, which means within acceptable percentage different. In new apartment 3, the measured heating energy consumption is 636.8kWh and the simulated data is 533.4kWh which is respectively 103.5kWh lower than the measured ones. It reveals the percentage difference between measured and simulated data was 16%, which is slightly higher than acceptable percentage different of 15%. This is may be caused by uncertain parameters and unknown variables. In new apartment 4, the measured heating energy consumption is 905.7kWh and the simulated data is 794.5kWh which is respectively 111.3kWh lower than the measured ones. It reveals the percentage difference between measured and simulated data was 12%, which means within acceptable percentage different. In new apartment 5, the measured heating energy consumption is 1017.5kWh and the simulated data is 868.6kWh which is respectively 148.9kWh lower than the measured ones. It reveals the percentage difference between measured and simulated data was 15%, which means within acceptable percentage different. In new apartment 6, the measured heating energy consumption is 598.6kWh and the simulated data is 504.9kWh which is respectively 93.8kWh lower than the measured ones. It reveals the percentage difference between measured and simulated data was 16%, which is slightly higher than acceptable percentage different of 15%. In new apartment 7, the measured heating energy consumption is 887.5kWh and the simulated data is 798.7kWh which is respectively 88.8kWh lower than the measured ones. It reveals the percentage difference between measured and simulated data was 10%, which means within acceptable percentage different.

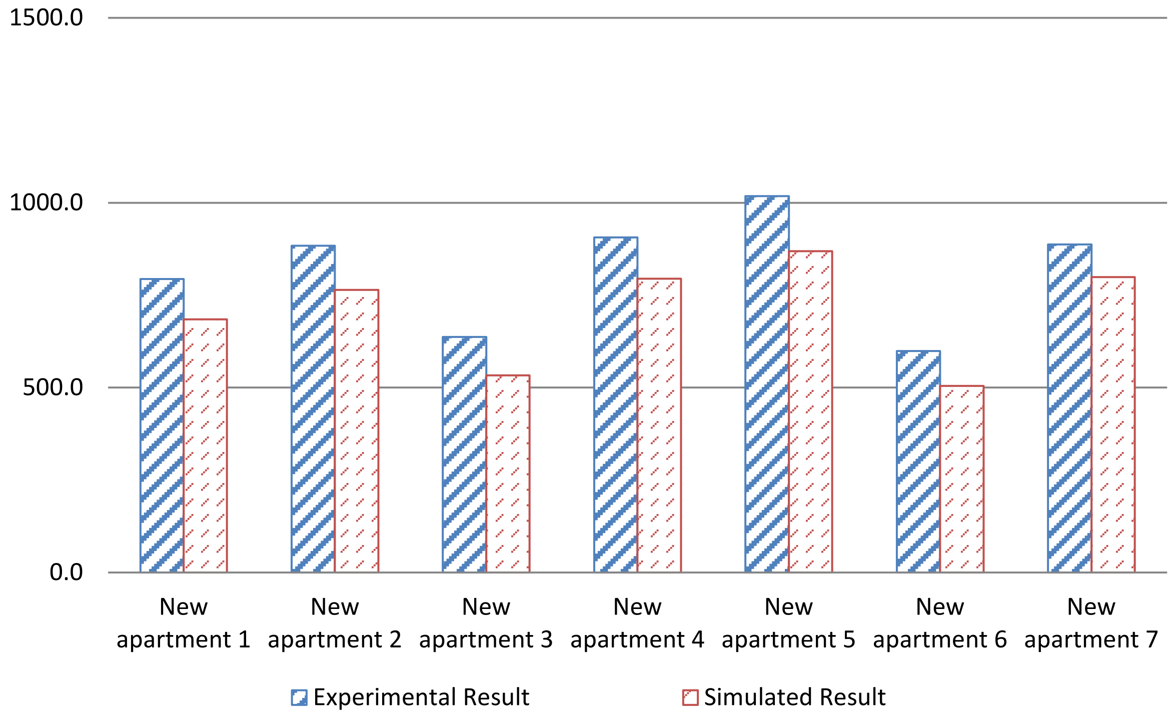


Figure 5.3 Actual and predict of energy consumption in new apartments

5.2.2 Validation of calculated heat loss after renovation in simulation models

According to the results from section 4.6, the correction of the air change values under reasonable conditions in practice. The air change rate in new apartments can be assumed as 0.76ac/h for simulation and in old apartments 1.51ac/h can be assumed for simulation. To correct the presentation of simulated results, consider reasonable of air tightness in new and old block models is exposed in table 5.1. Moreover, to ensure the accurate simulation results, the correction need to be presented. The corrected total energy consumption in old model blocks obtained when changing air change rate from 0.6 to 1.51ac/h. The simulation results of corrected energy consumption compared with the initial energy consumption, most deviation do not exceed 0.08%. In addition, the corrected total energy consumption in new model blocks obtained when changing air change rate from 0.6 to 0.76ac/h. The simulation results of corrected energy consumption compared with the initial energy consumption, most deviation do not exceed 0.06%. Thus, to ensure the accurate of simulated results of energy consumption, the reasonable infiltration rate regarded as input into modelling could be estimated.

Table 5.1 Comparison between initial energy consumption and corrected energy consumption in new and old block models

Old apartment model blocks	Initial energy consumption (ventilation heat loss calculated based on 0.6ac/h)	Corrected energy consumption (ventilation heat loss calculated based on 1.51ac/h)
1	1378.9 kWh	1387.28 kWh
2	1419.9 kWh	1428.28 kWh
3	1398.5 kWh	1406.87 kWh
4	1468.3 kWh	1476.63 kWh
5	1483.9 kWh	1492.29 kWh
6	1398.9 kWh	1437.24 kWh
7	1387.6 kWh	1395.91 kWh

New apartment model blocks	Initial energy consumption (ventilation heat loss calculated based on 0.6ac/h)	Energy consumption (ventilation heat loss calculated based on 0.76ac/h)
1	684.8 kWh	690.17 kWh
2	794.9 kWh	769.33 kWh
3	533.4 kWh	538.74 kWh
4	794.5 kWh	799.86 kWh
5	868.6 kWh	874.00 kWh
6	504.9 kWh	520.24 kWh
7	798.7 kWh	804.11 kWh

According to table 5.2, we can see infiltration rate after renovation used into simulation, the percentage difference between simulation data and measured data were improved slightly.

Table 5.2 Correction of input into simulated energy consumption model

Old apartment model block	Percentage difference between simulated energy consumption and measured energy consumption (%)	Percentage difference between corrected simulated energy consumption and measured energy consumption (%)
1	11.5	11.0
2	10.5	10.0
3	10.0	9.4
4	5.9	5.3
5	7.2	6.7
6	16.0	15.5
7	10.0	9.4

New apartment model block	Percentage difference between simulated energy consumption and measured energy consumption (%)	Percentage difference between corrected simulated energy consumption and measured energy consumption (%)
1	13.7	13.0
2	13.5	12.9
3	16.2	15.4
4	12.3	11.7
5	14.6	14.1
6	15.7	14.8
7	10.0	9.4

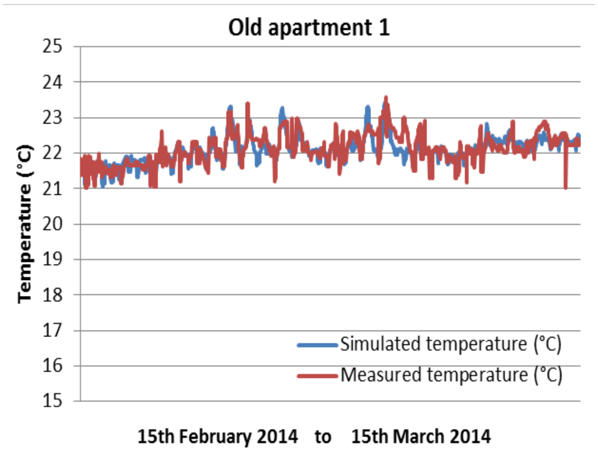
In original, the air change rate at 0.6ac/h regarded as default input into dynamic energy simulation of old apartment model blocks. For the correction, the air change rate change 1.51ac/h and in old apartment model block. Therefore, the total corrected simulated energy consumption could be estimated. As it can be noticed by table 5.2, the percentage different between corrected simulated model and actual measured energy consumption were decreased by 0.5%-1% compared with original simulation results. Furthermore, in original new apartment model blocks, the air change rate at 0.6ac/h regarded as default input into dynamic energy simulation. For the correction, the air change rate change to 0.76ac/h. It is therefore the total corrected simulated energy consumption could be estimated. The percentage different between corrected simulated model and actual measured energy consumption were decreased by 0.5%-1% compared with original simulation results.

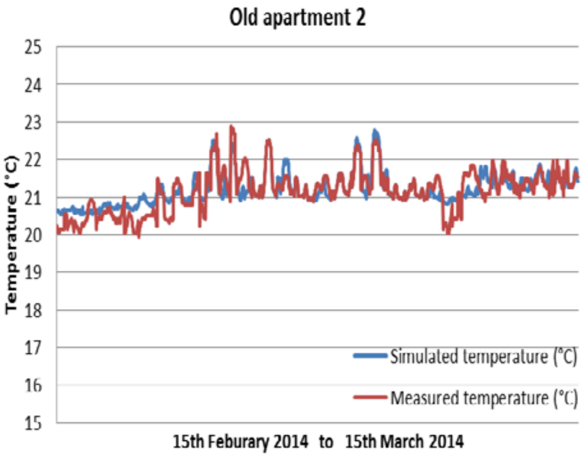
5.3 Analysis of new standard impact on potential energy saving

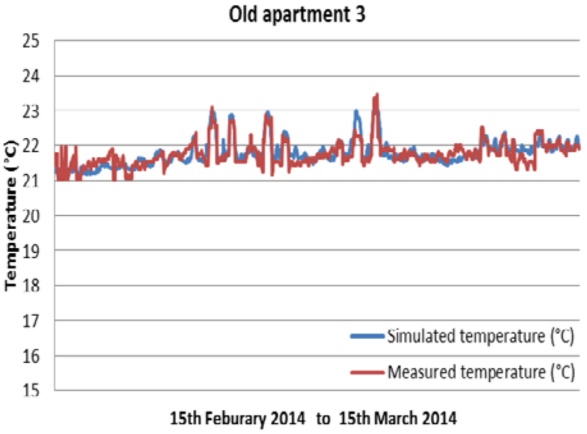
The study focus on evaluating different building design standards have effect on the thermal and energy performance of buildings, through a comparison of various potential main parameters (insulation level and construction, heating set-point, occupant window behaviour) of two types of residential buildings. The influence of new building standard on energy consumption should be examined by simulation. Therefore it is important to identify how each parameters effect on energy consumption and to predict the energy saving potential of each parameter on the heating energy consumption. The old apartment model blocks applied with new standard in simulation procedure by using four simulation scenarios were described in section 3.5.3. So that the validation of old apartment model blocks should be estimated by comparing measured data and simulated data.

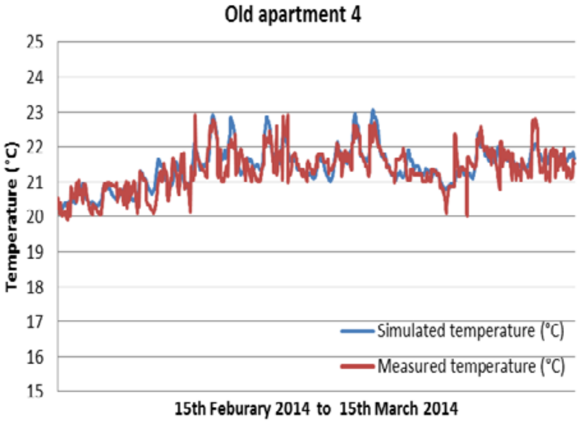
5.3.1 Comparison of measure and simulated indoor temperature in old and new apartment model blocks

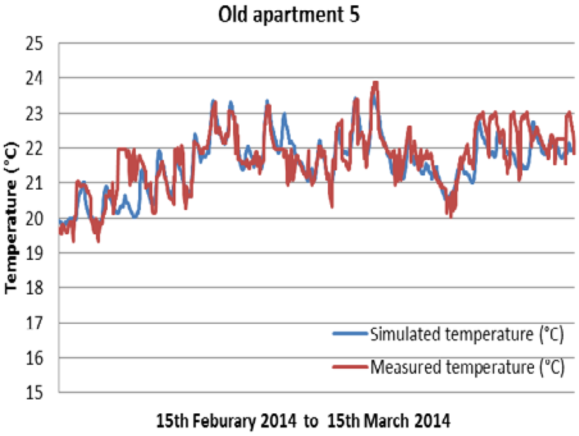
In order to evaluate cumbersome analysis of values, some statistical techniques can be used. It is intend to find explanations and identify the capabilities and limitations of the information provided by statistical indexes (Roberto & Vincent, 2014). The first validation assessment of building model, the indoor temperature were took place. Figure 5.4 reports the relationship between hourly simulated indoor temperatures obtain from model and hourly measured indoor temperatures in all old apartments during 15th February to 15th March during the heating season. The measured data is plotted against the simulated data are presented, indicating that the simulation model performed well on predicting indoor temperature in old apartments and provide an indication of the contribution of validation models as shown in Figure 5.4. It is therefore indicates that the simulation model can be a good predictor in old apartments. Therefore looking at the results from all simulation studies, the dynamic simulation results were agreement with the findings of the field measured data.

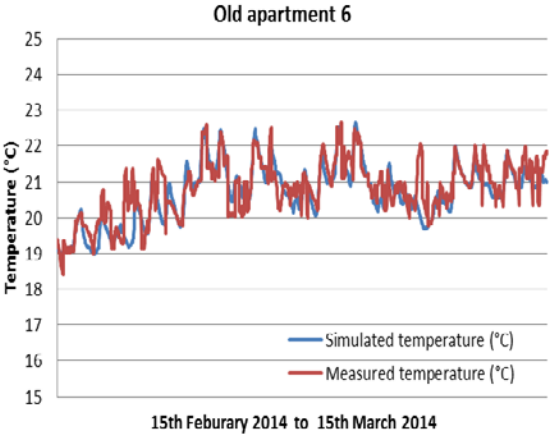












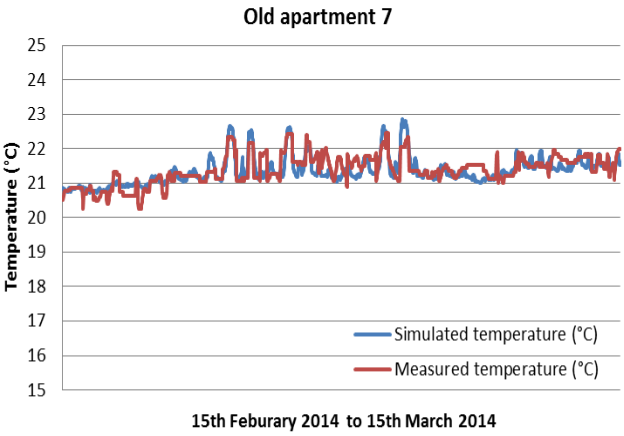
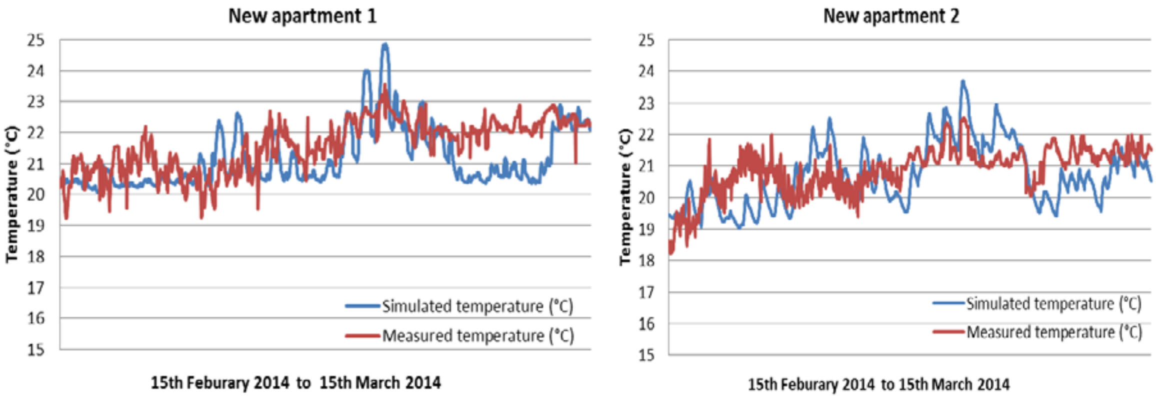


Figure 5.4 Correlations between measured hourly indoor temperature and simulated hourly indoor temperature in old apartments

Figure 5.5 reports the relationship between hourly simulated indoor temperatures obtain from model and hourly measured indoor temperatures in all new apartments during 15th February to 15th March during the heating season. For new apartments, the measured data is plotted against the simulated data are presented, indicating that the simulation model performed on predicting indoor temperature and provide an indication of the contribution of hour by hour validation models as shown in Figure 5.5. It is therefore indicates that the simulation model can be a predictor in new apartments as well. However compare with simulation model for old apartments, new apartments have individual heating control thus more uncertainty factor affected by occupants behaviour. Therefore looking at the results from all simulation studies, the dynamic simulation results were partly agreement with the findings of the field measured data.



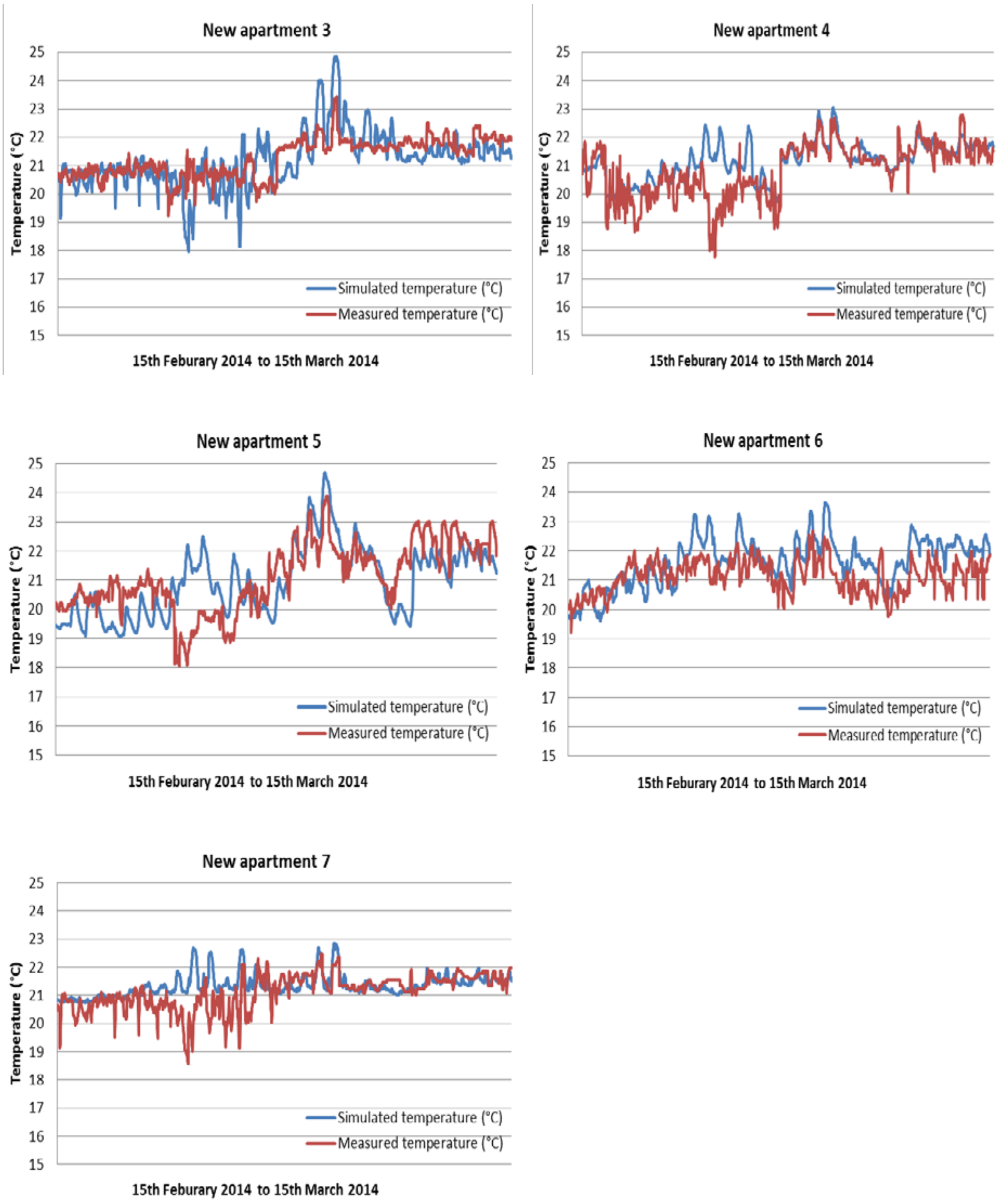


Figure 5.5 Correlations between measured hourly indoor temperature and simulated hourly indoor temperature in new apartments

5.3.2 Four simulation scenarios

After successful validation was undertaken, the energy consumption will be assessed with four scenarios. Four scenarios were simulated for old model block through the 15th February to 15th March 2014 period. As previous mentioned of findings of both measured and simulated results of energy consumption in new apartments are much lower than that in old ones. It can be related to the each parameters effect on energy consumption for both new and old apartments. Old apartment base on model block simulation run for four scenarios to estimate savings of apartments to further understand the how each parameters effect on energy consumption. It is therefore as mentioned in section 3.5.5. Four simulation scenarios were presented in table 5.3:

Table 5.3 Four simulation scenarios

Scenario 1	Base model + insulation level and construction employ with new standard
Scenario 2	Base model + heating set-point employ with new standard
Scenario 3	Base model + window operation measured in new apartments
Scenario 4	Base model + combine all interventions measured in new apartments

5.3.2.1 The simulation scenario 1

In order to evaluate the correlations between improved insulation design level in new standard and the heating energy demand reduction. The single-glazing window change to double-glazing and add insulation materials to walls in old apartment model blocks. Old model block applied with input of U-value and construction according to old building standard. Overall, the simulation results indicate that the energy consumption reduced from around 10036.1kWh to 7274.4kWh, reduction of energy is 2761.7kWh. It can be observed that for all old apartment model blocks, energy consumption reduced by 28% after improve insulation level and envelop.

The simulation results of each old apartment model block applied with new input parameters based on new design standard lead to significant reduction in heating energy consumption illustrated in Figure 5.6. In old apartment model block 1, the energy consumption reduced by 25% after improve insulation level. In old apartment model block 2, the energy consumption reduced by 27% after improve insulation level. In old apartment model block 3, the 27% energy-saving was achieved after improve insulation level. The simulation results from old apartment model block 4, the energy consumption reduced by 29% when improving insulation level. The simulation results from old apartment model block 5, the energy consumption reduced by 27% when improving insulation level. The simulation results from old apartment model block 6, the energy consumption reduced by 28% when improving insulation level. The simulation results of old apartment model block 7 shows that 28% of energy saving after increase insulation level. It demonstrated that different insulation could have obvious influence on the heating energy consumption in this study. Therefore simulation results exposed that the implementation of the proposed energy efficiency improvements in the old apartment model block would provide heating energy savings. Many previous studies have been confirmed that the insulation level has significant effect on energy demand in Chinese residential buildings. Previous study was found that the better insulated in new buildings lead to the more energy saving and could save money (Liu & Liu, 2011).

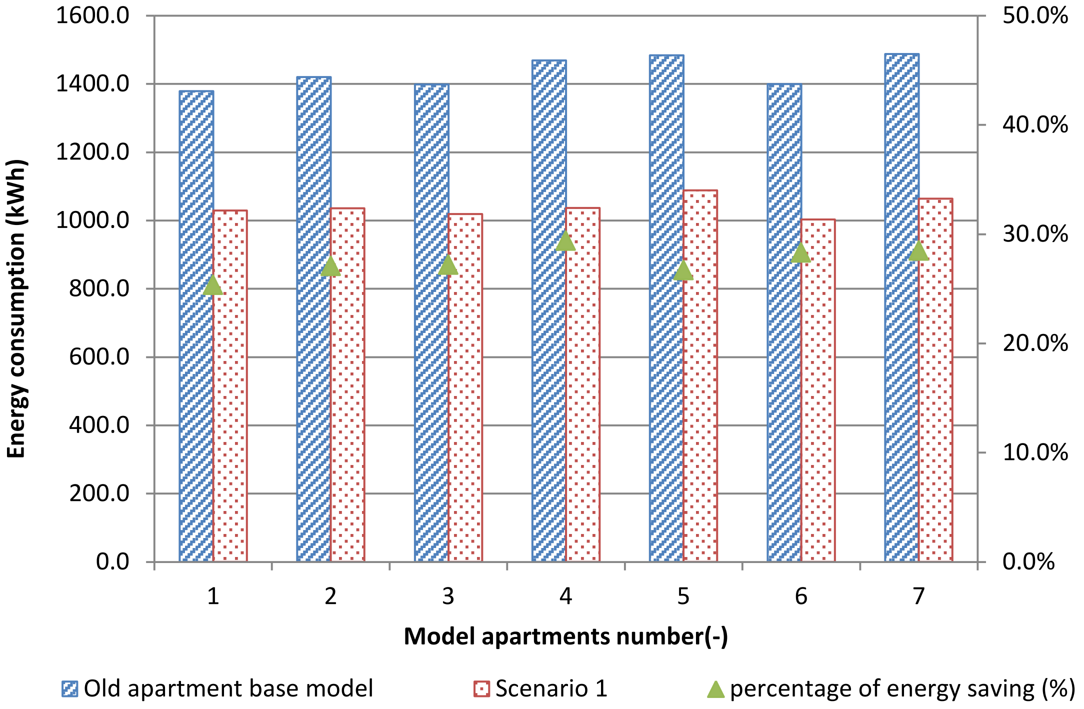


Figure 5.6 Simulation of energy saving by using scenario 1

5.3.2.2 The simulation scenario 2

In order to evaluate the correlations between heating set-point and the heating energy demand reduction. Old apartment model blocks applied with new input of heating set-point temperatures based on measured mean indoor temperature in new apartments. Overall, the simulation results indicate that the energy consumption reduced from around 10036.1kWh to 8848.5kWh, reduction of energy is 1187.6kWh. It can be observed that for all old apartment model blocks, energy consumption reduced by 12% after reduce heating set-point standard.

The simulation results of each old apartment model block applied with new input parameters based on new design standard lead to significant reduction in heating energy consumption illustrated in Figure 5.7. In old apartment model block 1, the energy consumption reduced from around 1378.9kWh to 1223.8kWh and it lead to decrease by 13% after changing heating set-point. In old apartment model block 2, the energy consumption reduced from around 1419.9kWh to 1236.8kWh and it lead to decrease by 15% after changing heating set-point. There is 11% reduction of energy consumption after changing heat-set point in old apartment model block 3. Energy consumption decreased from 1398.5kWh to 1259.5kWh. The simulation results from old apartment model block 4, the energy consumption reduced from 1468.9kWh to 1301.8kWh and it lead to 13% of energy saving after changing heating set-point. The simulation results from old apartment model block 5, the energy consumption reduced from 1483.9kWh to 1305.4kWh and it lead to 14% of energy saving after changing heating set-point. There is 13% reduction of energy consumption after changing heat-set point in old apartment model block 6. Energy consumption decreased from 1398.9kWh to 1238.9kWh. The simulation results of old apartment model block 7 shows that energy consumption reduced from 1487.7kWh to 1282.9kWh and it lead to 16% of energy saving after changing heating set-point. It demonstrated that old apartment model blocks use with new heating set-point can effectively reduce the heating energy consumption by 13% averagely. Heating set point play an important role in adjusting indoor temperature. In new apartments, occupants adjust TRVs set-point to achieve satisfied indoor environment. In addition, the experimental results show that the heating set-point temperature in new apartments were lower. As previous researchers found that the different heating control systems have significantly effect on occupant behaviour. The results of previous studies found that the mean temperature setting in dwellings with a thermostat is slightly lower than that in dwellings without a thermostat. In addition, the heating set-point has directly impact on heating energy consumption (Guerra-Santin & Itard, 2010; Santin, et al., 2009; Shipworth, et al., 2010). This is may be explained that the lower heating set-point have influence on the heating energy consumption in our study.

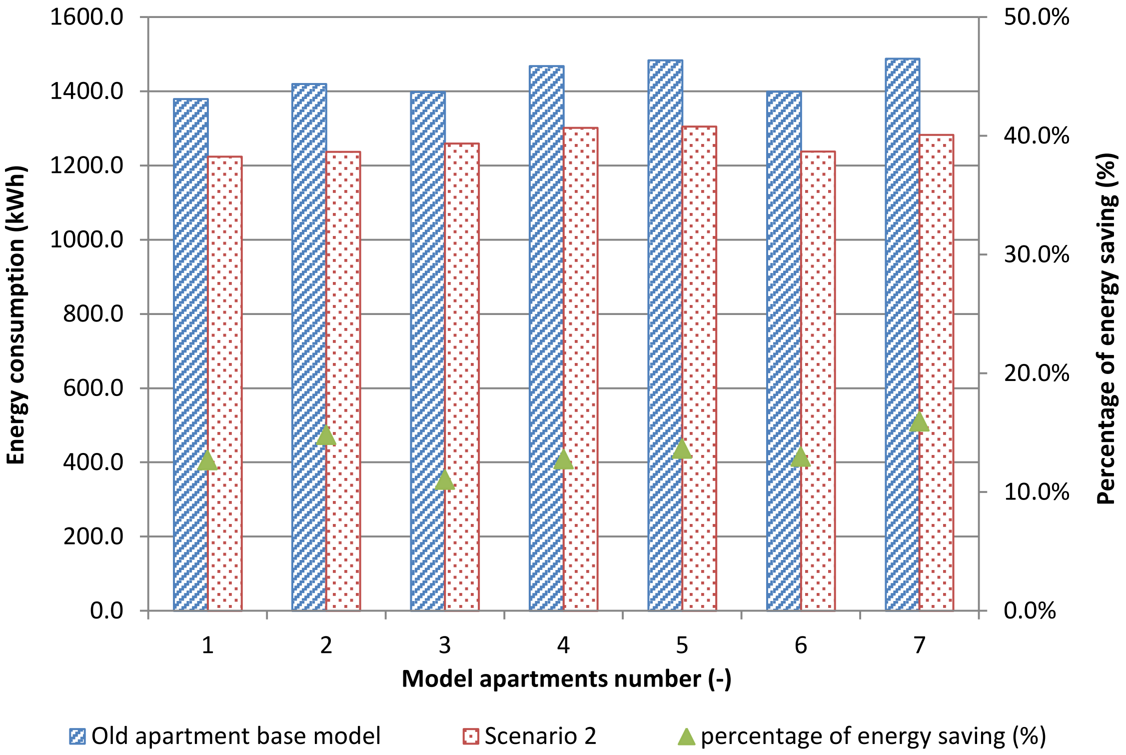


Figure 5.7 Simulation of energy saving by using scenario 2

5.3.2.3 The simulation scenario 3

As mentioned above, the field real measured data reflect that the windows in the new apartments, they were opened only for 29% of the monitoring time. Furthermore From the comparison of the experimental result shows that mean indoor air temperature in old apartments are higher than that in new apartments which is respectively 1.9°C. Occupants only can open windows to reduce indoor climates and it is therefore to estimate the window operation effect on the heating energy consumption. Old apartment model blocks applied with input of window operation measured in new apartments. Overall, the simulation results indicate that the energy consumption reduced from around 10036.1kWh to 8994.9kWh, reduction of energy is 1041.1kWh (see in Figure 5.8). It can be observed that for all old apartment model blocks, energy consumption reduced by 10% after reducing window opening. The simulation results of old apartment model block 1 confirms less of window opening can decrease heating energy consumption by 10%. The energy consumption reduced from around 1378.93kWh to 1248.0kWh, reduction of energy is 130.9kWh. In old apartment model block 2, the energy consumption reduced by 10% when window opened less and reduction of energy is 143.5kWh. In old apartment model block 3, the energy consumption reduced by 11% when window opened less and reduction of energy is 157.5kWh. The simulation results of old apartment model block 4 confirms less of window opening can decrease heating energy consumption by 12%. The energy consumption reduced from around 1468.2kWh to 1295.4kWh. In old apartment model block 5, the energy consumption reduced from around 1483.9kWh to 1335.8kWh and it lead to decrease by 10% after reduce window opening. The simulation results of old apartment model block 6 confirms less of window opening can decrease heating energy consumption by 9%. In old apartment model block 7, the energy consumption reduced by 11% when window opened less and reduction of energy is 159.8kWh.

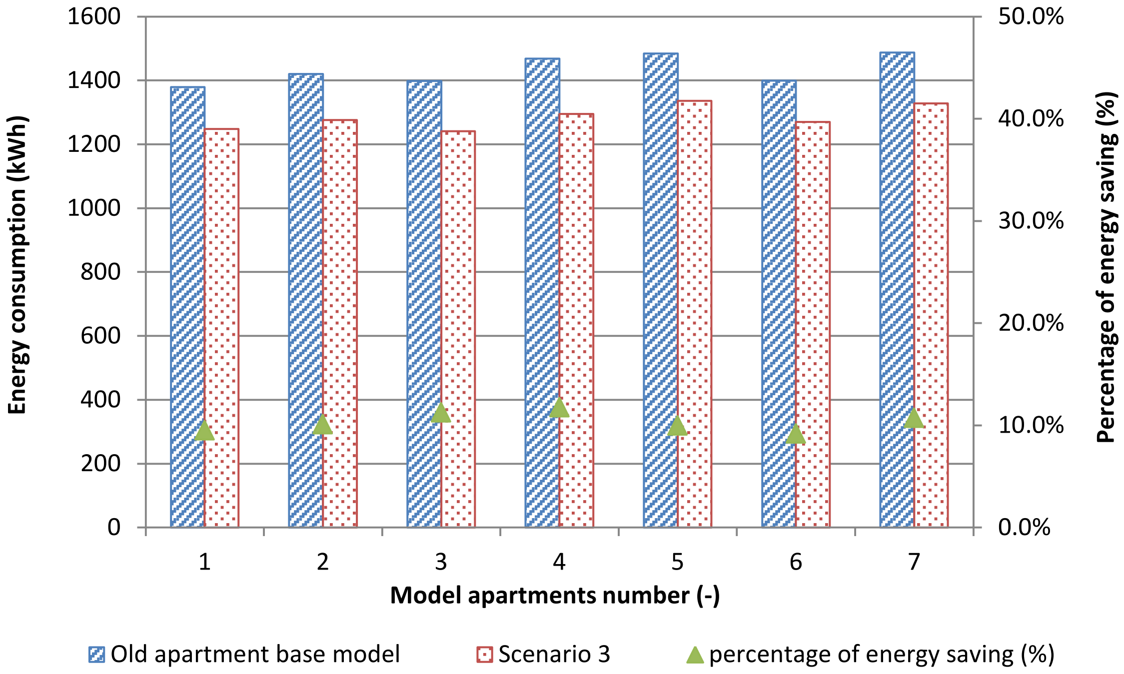


Figure 5.8 Simulation of energy saving by using scenario 3

5.3.2.4 The simulation scenario 4

In order to evaluate all interventions combined in simulated models, the results indicated that the energy consumption reduced from around 10036.1kWh to 5151.8kWh, reduction of energy is 4884.3kWh (given in Figure 5.9). It can be observed that for all old apartment model blocks, energy consumption reduced by 48.6% when combine all interventions in old apartment models.

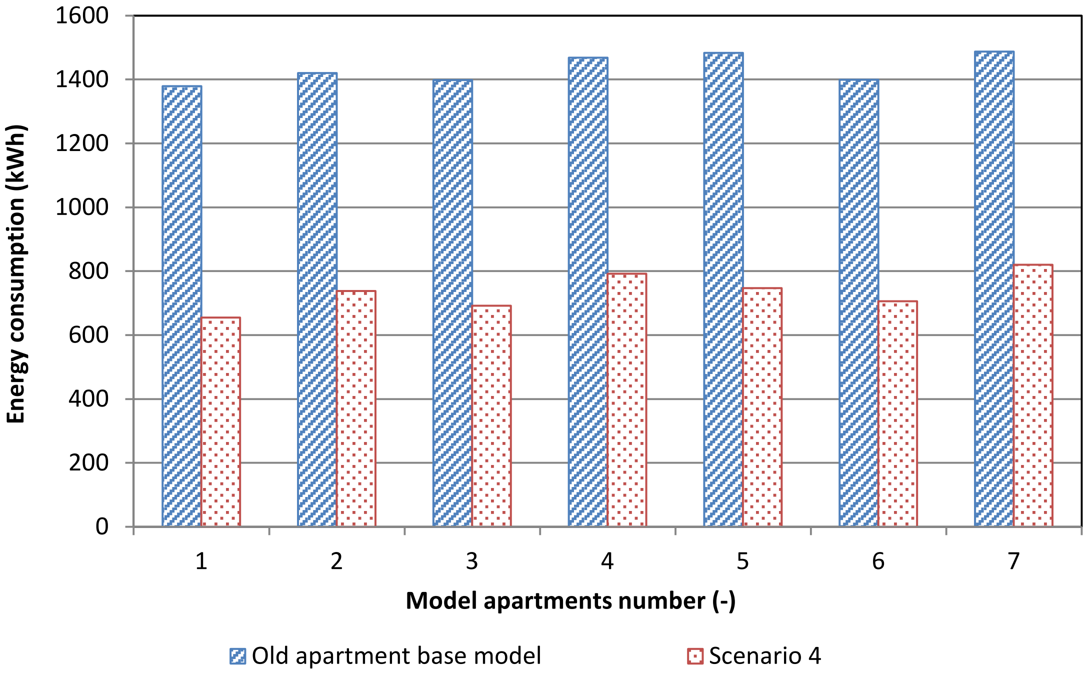


Figure 5.9 Simulation of energy saving by using scenario 4

The overall simulated results show that each renovated parameters leading to energy saving. Furthermore it reveals that each parameter (insulation level, construction, heating set-point and window operation) have obvious influence on energy consumption. Overall, the simulation results indicate that the energy consumption reduced by 28% after improve insulation level and envelop. Energy consumption reduced by 12% due to heating control system with lower heating set-point. In addition, energy consumption reduced by 10% due to less window opening. It is therefore the insulation level contribute highest energy-saving effect of all parameters in simulation. This implies the new apartments complying with new heating control system and new heat bill system can lead to obvious energy saving for heating in winter compared with old apartments.

5.4 Summary

This chapter presents the analysis of simulation results and it was found that the measured and simulated data presented acceptable level of validity. Furthermore the measured energy consumption and simulated energy consumption were compared. In particular, the analysis was focused on each factor effect on energy consumption and indoor thermal conditions were discussed. Generally, it was found that for all apartments the measured heating energy consumption and the simulated data which are respectively lower than the measured ones.

After successful validation was undertaken, prioritization of insulation level effect on energy consumption in old apartments was assessed by simulation. To ensure the accurate of simulated results of energy consumption, the reasonable infiltration rate regarded as input into modelling were estimated. The simulation results of corrected energy consumption compared with the initial energy consumption, most deviation do not exceed 0.06%-10%.

Generally, the simulation results obtained from this study indicated that the better insulation level making more substantial energy saving and energy consumption reduced by 28% after improve insulation level and envelop. Energy consumption reduced by 12% after reduce heating set-point standard. In addition, the simulation results confirmed less of window opening can decrease heating energy consumption by 10%. It can be observed that for all old apartment model blocks, energy consumption reduced by 48.6% when combine all interventions in old apartment models.

Chapter 6

FIELD STUDY OF THERMAL COMFORT

6 Field study of thermal comfort

6.1.1 Introduction

This chapter describes the results of thermal comfort measurements made in both new and old apartments. Four physical factors, thermal sensation for new and old buildings were compared respectively. As mentioned in the review chapter 2, reform and implementation of the new heating and billing system has been incorporated into new built residential buildings. It is therefore important to identify the influence of each potential factor on occupants' thermal comfort. In this chapter the detailed information regarding results of thermal comfort in old apartments are compared with the results of thermal comfort in new apartments. The results of thermal comfort study through physical measurements and questionnaire survey are provided. This was done to identify the validity of the PMV model for comfort predictor in new and old apartments.

6.1.2 Four environmental factors results

6.1.2.1 Indoor climates in old and new apartments

Statistical summaries of the variations of indoor environmental parameters in old and new apartments can be seen from table 6.1, the results show that the mean indoor temperature in all old apartments is 22.5°C and the indoor air temperature in new one is 20.7°C which is respectively 1.8°C lower than the value measured in old apartments. The mean radiant temperature (MRT) ranged from 22.5°C to 23.3°C in old apartments, whilst in new apartments, the mean value of MRT with a ranged of 19.8°C–21.9°C. The mean Relative humidity obtained in the old apartments was 48.3%, which is close to that 43.5% in the new apartments. The indoor air velocity in old apartments ranged from 0.03m/s–0.05m/s respectively in new apartments has value range from 0.01m/s–0.06m/s. Meanwhile, shows that the majority of air velocity in both new and old apartments was low, with a mean value of 0.056 m/s, which was not more than 0.15 m/s, which meets the winter thermal comfort standard (Wang, et al., 2011).

Table 6.1 Statistics of indoor environmental parameters in old and new apartments

		Old apartments	**New apartments**
Air temperature (°C)	Mean	22.5	20.7
	Max	24.2	23.1
	Min	21.1	20.2
	SD	1.86	1.21
Relative humidity (%)	Mean	48.3	43.5
	Max	57	51.2
	Min	32.4	28.9
	SD	8.7	7.08
Air velocity (m/s)	Mean	0.05	0.04
	Max	0.06	0.05
	Min	0.01	0.03
	SD	0.04	0.02
Mean radiant temperature (°C)	Mean	22.8	21.3
	Max	25.6	23.5
	Min	20.1	20.9
	SD	2.51	1.9

In addition, Table 6.2 descripts the indoor air temperature for 7 new apartments and 7 old apartments during investigation period are given below. The mean outdoor air temperature is 8.9°C, the maximum and minimum temperatures are 27.7°C and -1.9°C respectively during the investigation. According to the results of questionnaires, in old apartments, the majority of occupants respond that the windows were opened because it was hot inside apartments and they prefer to have cooler indoor environments.

Table 6.2 Summaries of indoor temperature data in each new and old apartment

Residential Building Types	Apartment No.	Indoor Air Temperature		
		Mean	Max.	Min.
Old apartments	1	22.2	23.6	16.7
	2	22.6	24.7	18.1
	3	22.4	23.5	18.2
	4	22.5	25.2	16.1
	5	22.9	24.8	17.3
	6	22.2	25.7	15.7
	7	22.7	25.1	17.2
New apartments	1	21.0	23.4	17.4
	2	20.9	22.4	17.5
	3	20.8	22.2	15.8
	4	21.1	22.2	17.3
	5	21.6	22.6	16.1
	6	19.7	23.2	15.8
	7	19.6	23.4	15.9

6.1.2.2 Clothing insulation

The statistical summaries of clothing insulation values were taken from what occupants themselves as estimated from clothing insulation lists. Based on the chair insulation effect on occupants, in this study the insulation of the chair is assumed to be 0.35clo as all participants were sitting on a fabric sofa during the survey (de Dear & Brager, 1997). Clothing insulation value ranged from 0.78clo to 1.197clo with a mean value of 0.9clo in new apartments. In old apartments, the clothing insulation values varied from 0.608clo to 1.28clo with a mean value of 0.79clo. Clothing is a behavioural adjustment that directly affects heat balance (RP-884) and responds one of key thermal adaptive responses (de Dear & Brager, 1997). Figure 6.1 show that the relations between clothing insulation level and indoor temperature. From liner correlation the coefficient of determination R^2 can be observed as 0.12 for old apartments and 0.08 for new apartments.

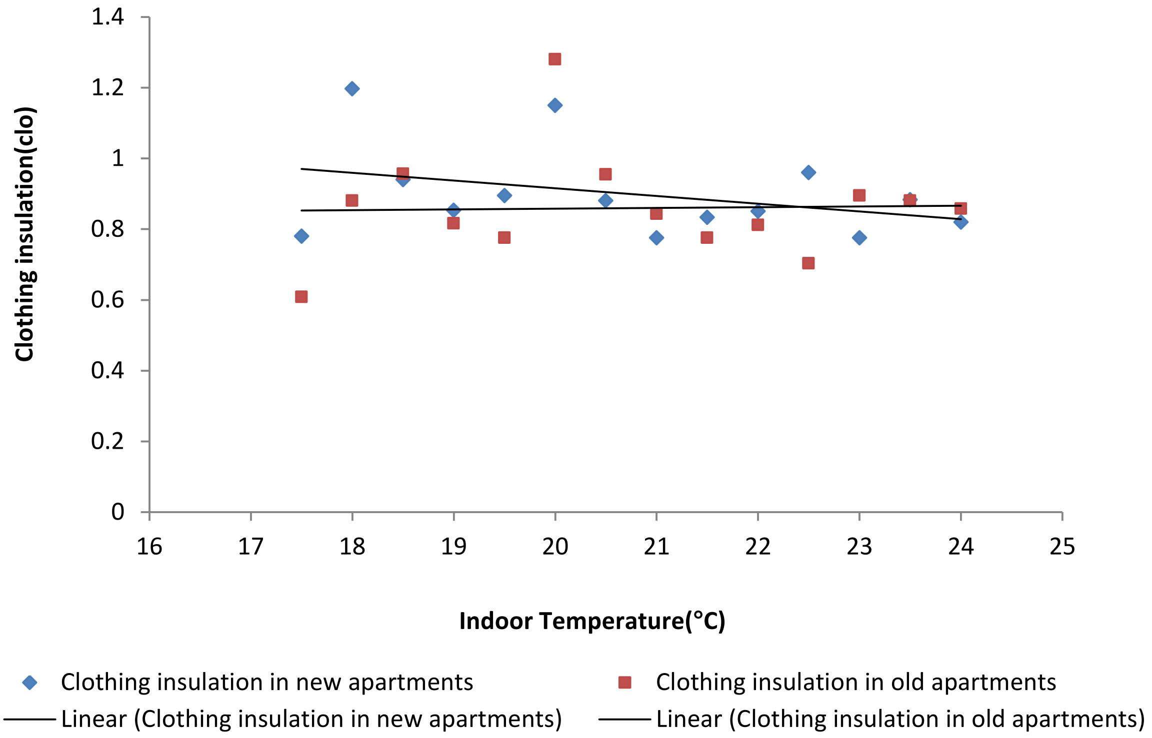


Figure 6.1 Comparison of clothing insulation between old apartments and new apartments

6.1.3 Comparison of thermal sensation votes in new and old apartments

Figure 6.2 shows that the occupants' overall the thermal sensation voted for the surveyed new and old apartments. For the new apartments, majority of subjects voted the range from slightly cool (-1) to slight warm (+1). It can be seen that majority of occupants feel between neutral and slightly cool. However, the greater number of occupants in old apartments voted the range from slightly warm (+1) to warm (+2) and also have 16 percentage of occupants voted hot (+3) that much more than none of subjects vote hot (+3) in new apartments. From Figure 6.2 indicated that in old and new apartments, majority of occupants voted within the central three categories against that the ASHRAE Standard 55-2004 specified that an acceptable thermal environment should have 80% of occupants vote for the central categories (-1,0,+1).

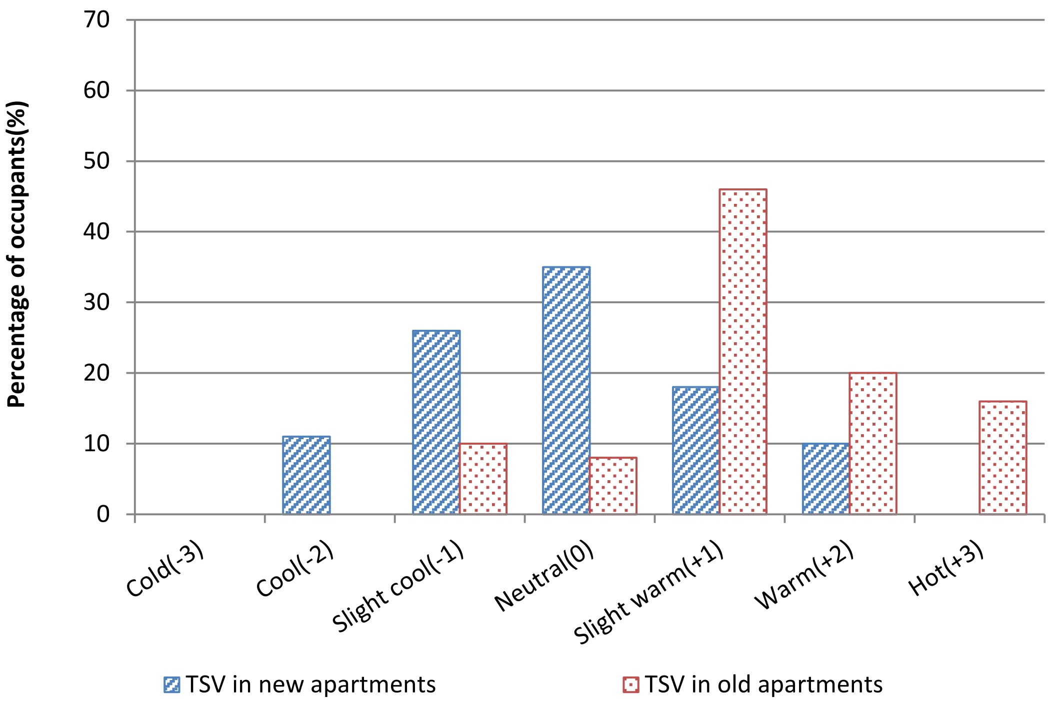


Figure 6.2 Comparison of thermal sensation vote of occupants in new and old apartments

6.1.4 Investigating validity of PMV model

The correlation between the calculated PMV and the reported AMV are presented in Figure 6.3. The correlation coefficients in new and old apartments are 0.70 and 0.73 respectively. It indicate that the PMV model performed well on predicting occupants' thermal comfort in both new and old apartments and provide an indication of the contribution of Fanger model. According to de Dear and Brager pointed that thermal adaptation can be achieved from three categories: behavioural adjustment, physiological acclimatization and psychological habituation (Brager & de Dear, 1998). Evidence reviewed in this paper indicated that thermal sensations of occupants have strong correlation to psychological and behavioural adjustment. Discrepancies observed could mean that there are psychobiological adaptations factors involved in thermal comfort of occupants in new apartments may have higher acceptable, result from controllability of heating system. Furthermore, In this study, occupants in new apartments are able to achieve their psychological expected or satisfied indoor environment via adjust TRVs set-point, thus they respond more acceptable of indoor environment than those in old ones. In addition, the details of heating behaviour were analysed in section 4.4, and results show that heating set-point behaviour strongly impact on energy consumption. Oppositely, occupants in old apartments have no opportunity to control environmental set point by control systems. Therefore, they respond discomfort with their indoor environments, in particular, they only can open window when room were overheated. It also can be consider that difference of the heating bill payment between new and old apartments. This is can be due to the occupants in new apartments can potential reduce indoor set point by using TRVs to save energy use related to less heating bill payment. Thus they provide better thermal responses. Evidence concluded in this study show that new building standard lead to better thermal comfort of occupants compared with old one.

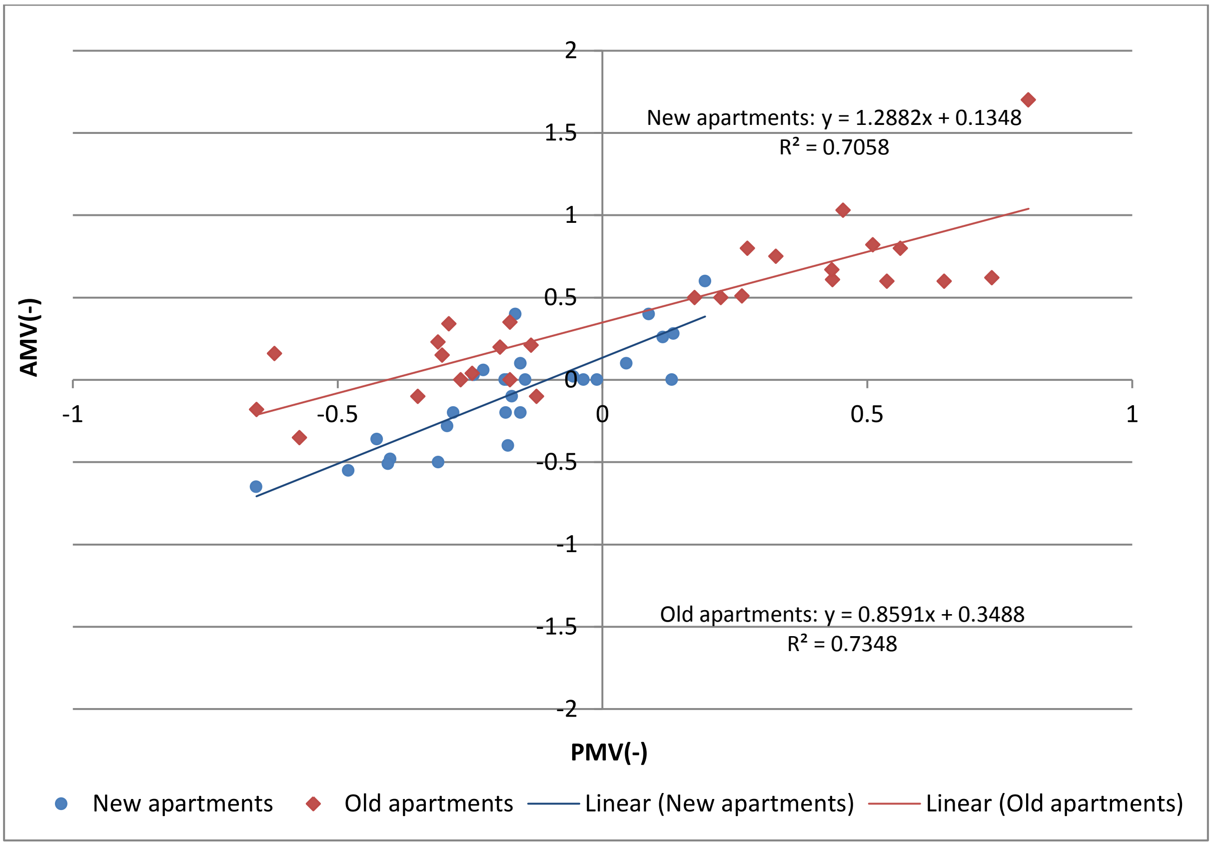
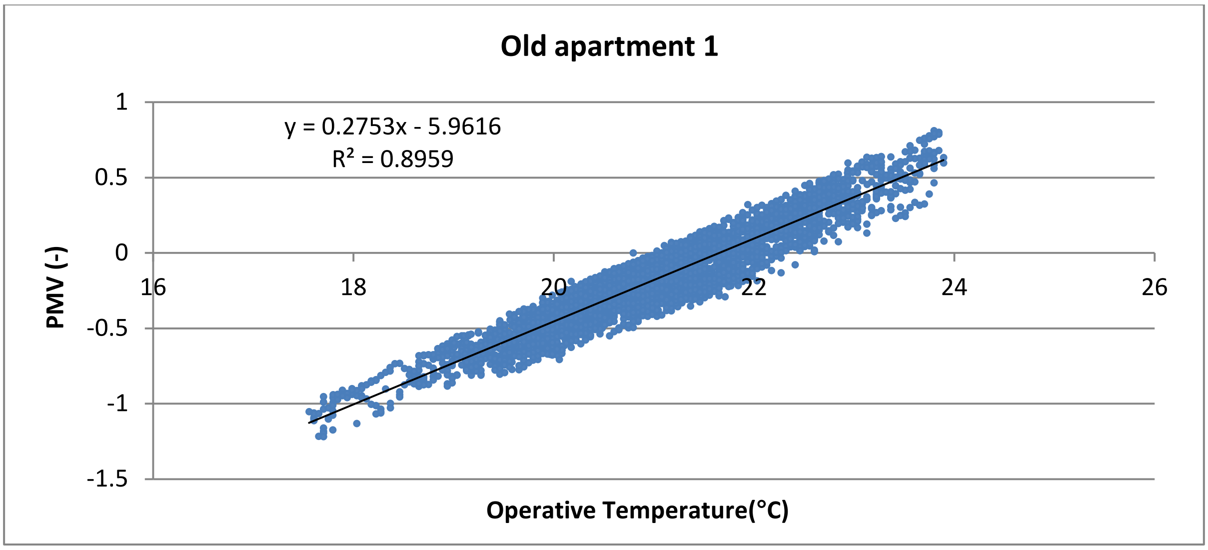
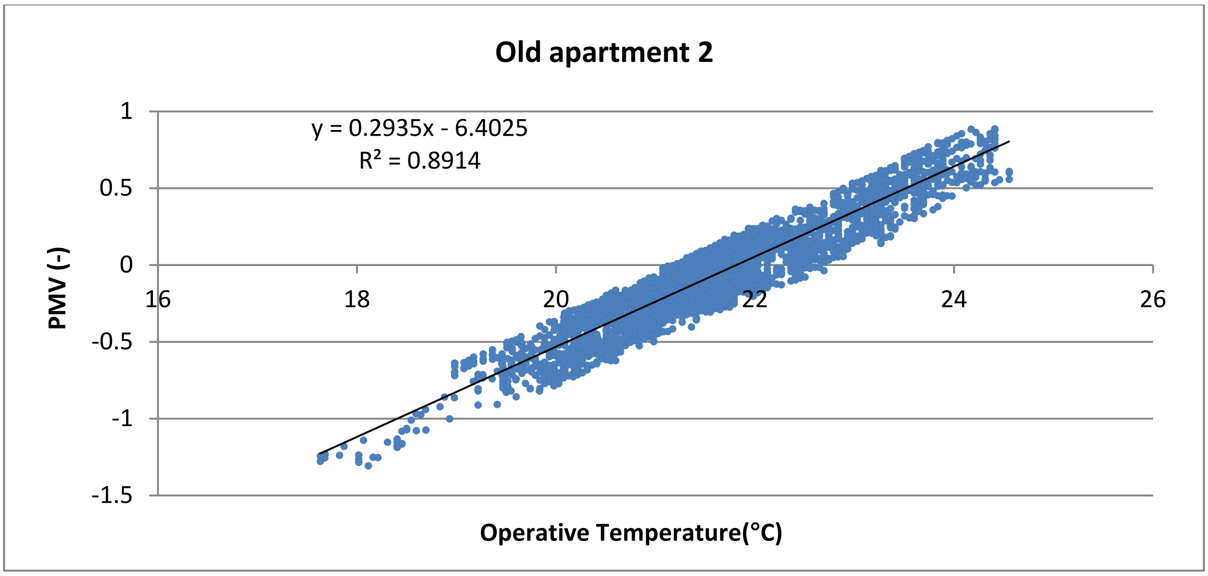


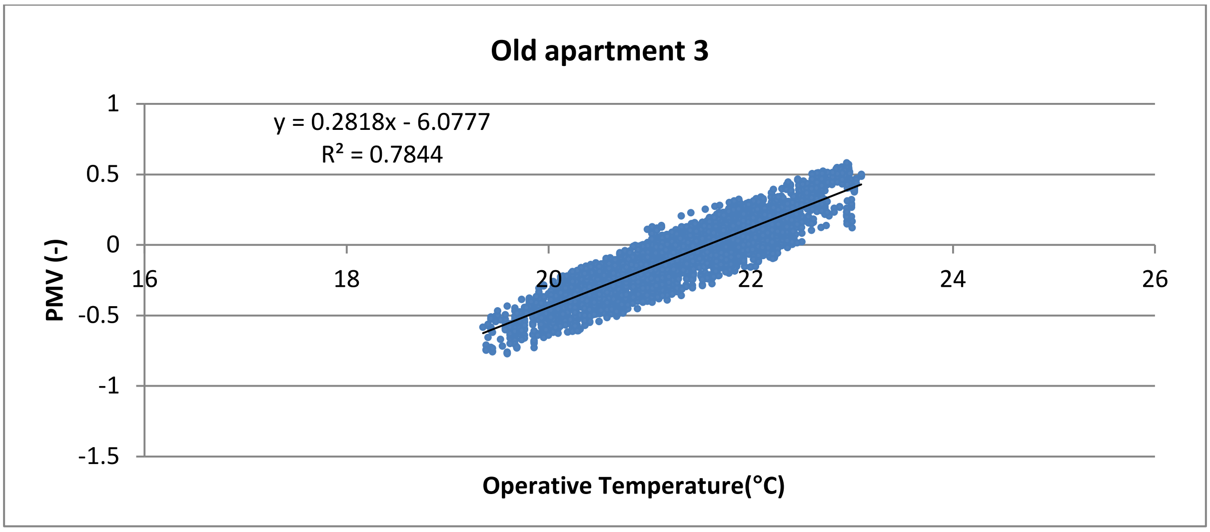
Figure 6.3 Regression lines of AMV versus PMV in new and old apartments

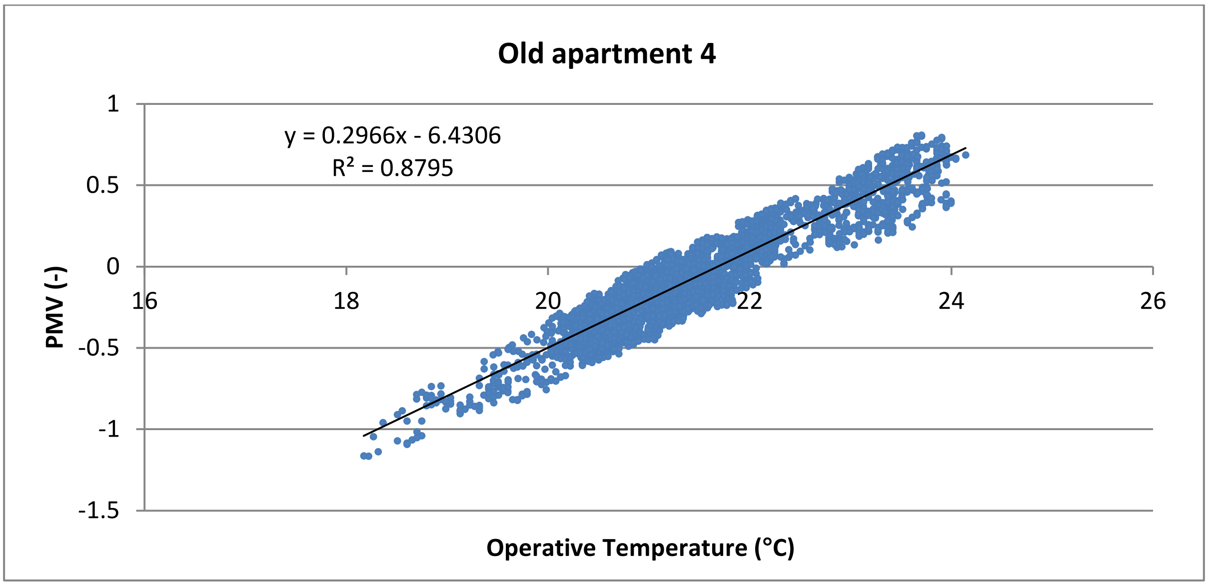
6.1.4.1 Predicted neutral temperature in old apartments during investigation periods

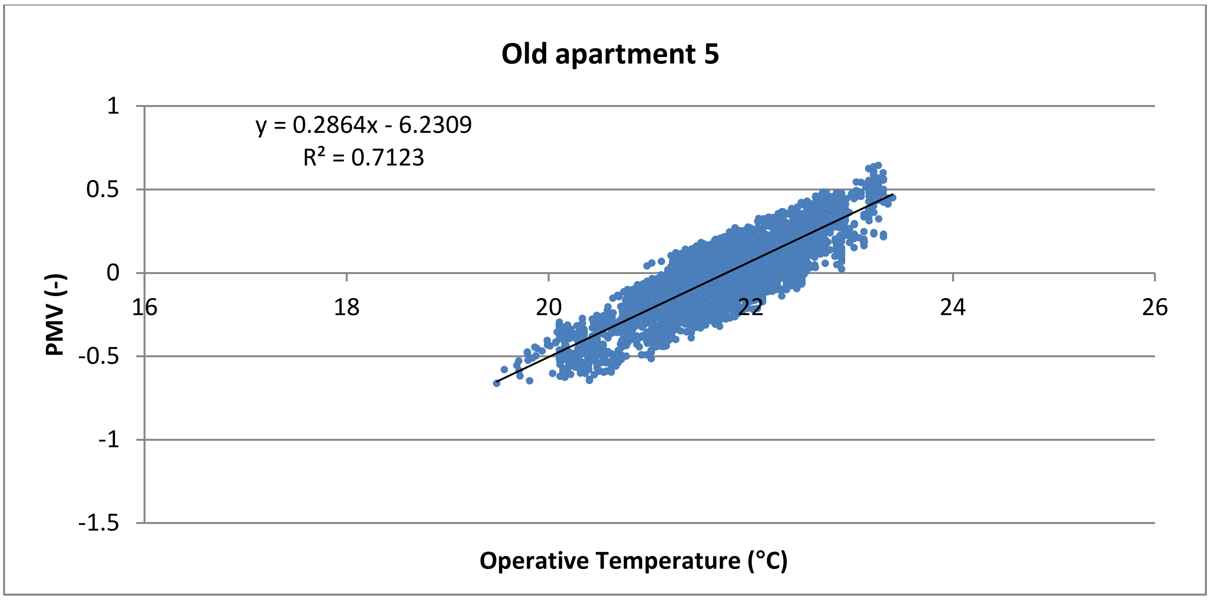
As mentioned above of Figure 6.3 indicates that the PMV model performed well on predicting occupants' thermal comfort in both new and old apartments and can be considered to be applicable in this study. In addition, hourly Indoor air temperature and relative humidity were measured by data logger by every ten minutes in each apartment. The mean radiant temperature was estimated from globe temperature measured by using about 38mm black ball global temperature thermometer. Table 6.1 shows the results of each measured parameters, it was found that the slightly difference between indoor air temperatures and global temperatures in both type of apartments. Indoor air velocities were measured by hot-wire anemometer and the mean value is 0.05. According to interview survey in each old apartment, the mean clothing insulation values of 0.79clo was set to calculate PMV values. The metabolic rate was considered to be approximately 1.1met in each apartment in PMV model. Therefore the hourly PMV values can be calculated based on hourly air temperature, hourly global temperature and relative humidity, mean air velocity, fixed mean clothes insulation and metabolic rate in all old apartments during whole experimental period time can be worked out.

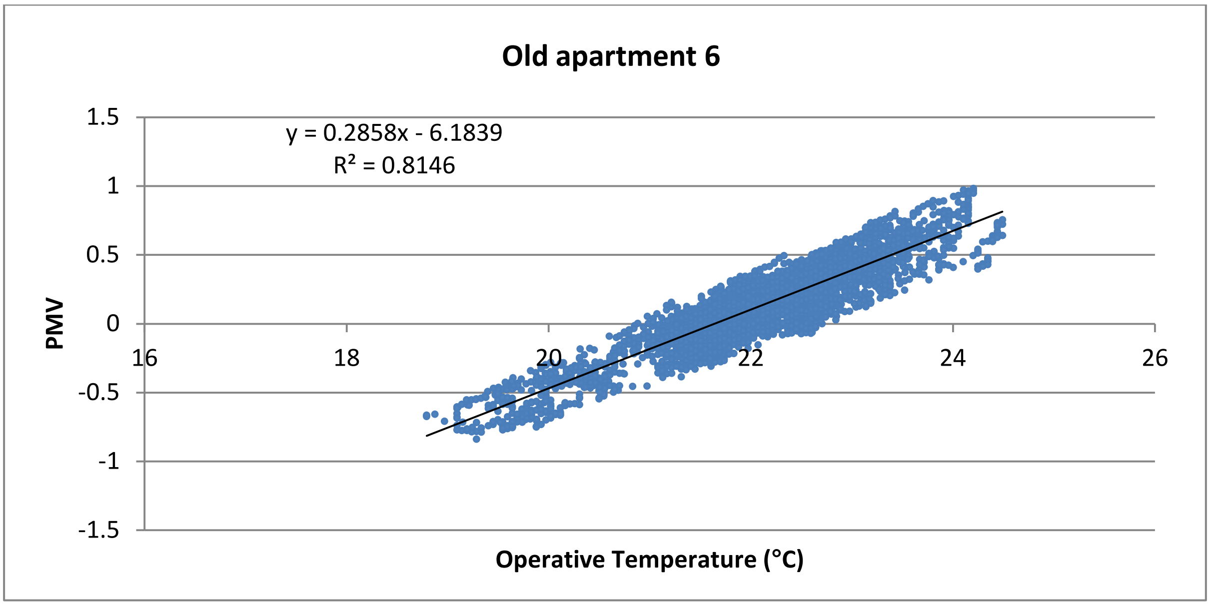



Old apartment 2
y = 0.2935x - 6.4025
R² = 0.8914
PMV (-)
1
0.5
0
-0.5
-1
-1.5
16
18
20
22
24
26
Operative Temperature(°C)


Old apartment 3
y = 0.2818x - 6.0777
R² = 0.7844
PMV (-)
1
0.5
0
-0.5
-1
-1.5
16
18
20
22
24
26
Operative Temperature(°C)


Old apartment 4
y = 0.2966x - 6.4306
R² = 0.8795
PMV (-)
1
0.5
0
-0.5
-1
-1.5
16
18
20
22
24
26
Operative Temperature (°C)


Old apartment 5
y = 0.2864x - 6.2309
R² = 0.7123
1
0.5
0
-0.5
-1
-1.5
PMV (-)
16
18
20
22
24
26
Operative Temperature (°C)


Old apartment 6
y = 0.2858x - 6.1839
R² = 0.8146
1.5
1
0.5
0
-0.5
-1
-1.5
PMV
16
18
20
22
24
26
Operative Temperature (°C)

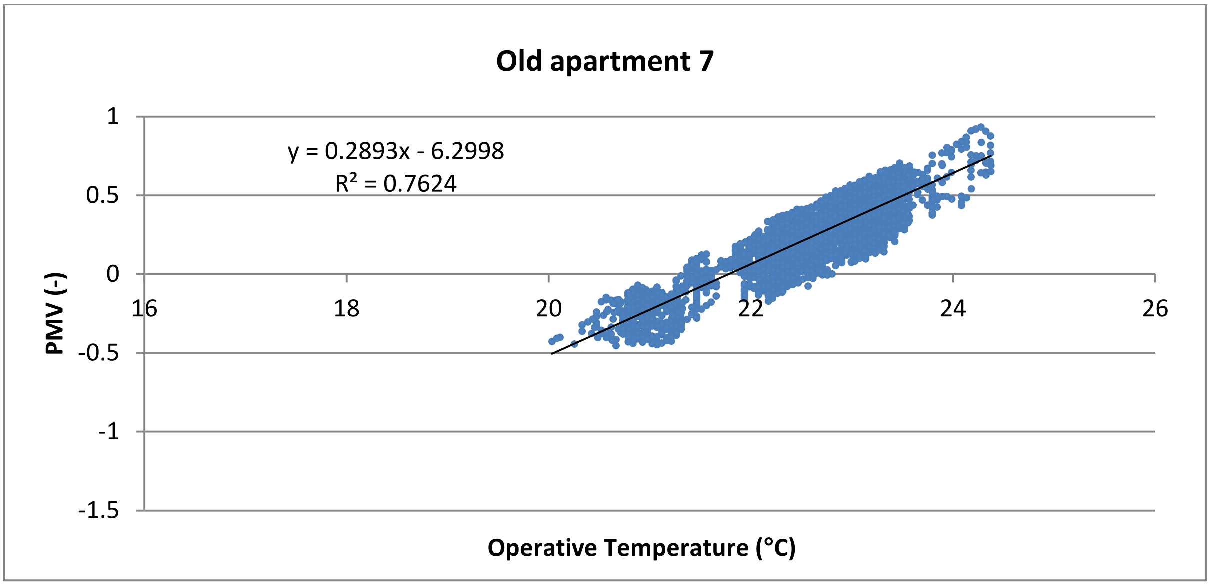


Figure 6.4 linear regressions of operative temperature and PMV values in all old apartments

Figure 6.4 shows that the PMV calculated according to Fanger's model plotted with operative temperature in each old apartment. The linear regression equation for each apartment that are

Old apartment 1: PMV= $0.2753T_{op} – 5.9616$, R^2= 0.8959

Old apartment 2: PMV= $0.2935T_{op} – 6.4025$, R^2= 0.8914

Old apartment 3: PMV= $0.2818T_{op} – 6.0777$, R^2= 0.7844

Old apartment 4: PMV= $0.2966T_{op} – 6.4306$, R^2= 0.8795

Old apartment 5: PMV= $0.2864T_{op} – 6.2309$, R^2= 0.7723

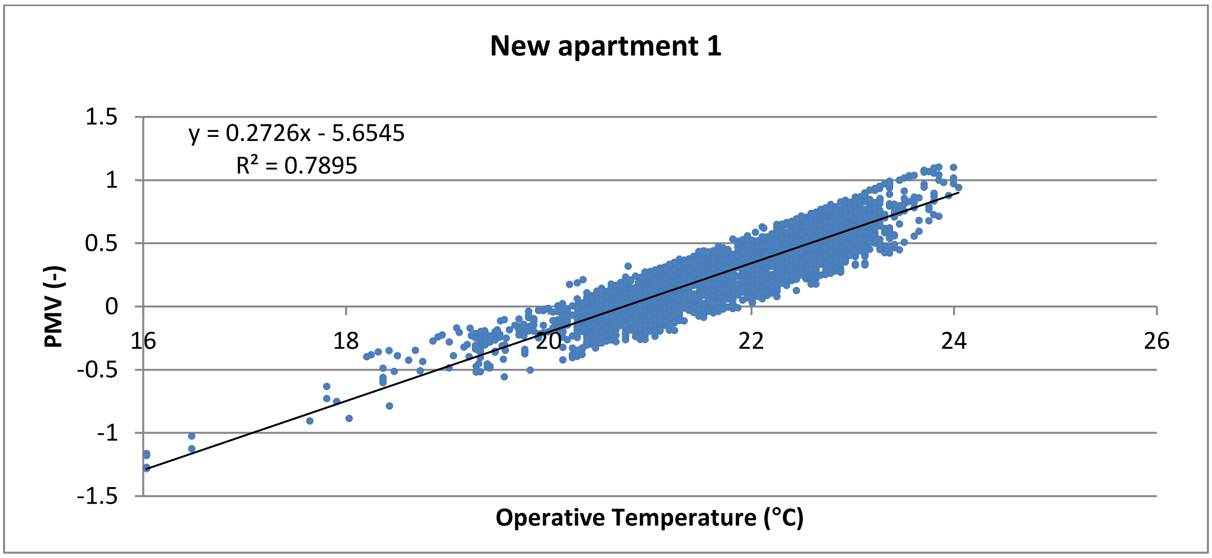
Old apartment 6: PMV= $0.2858T_{op} – 6.1839$, R^2= 0.8149

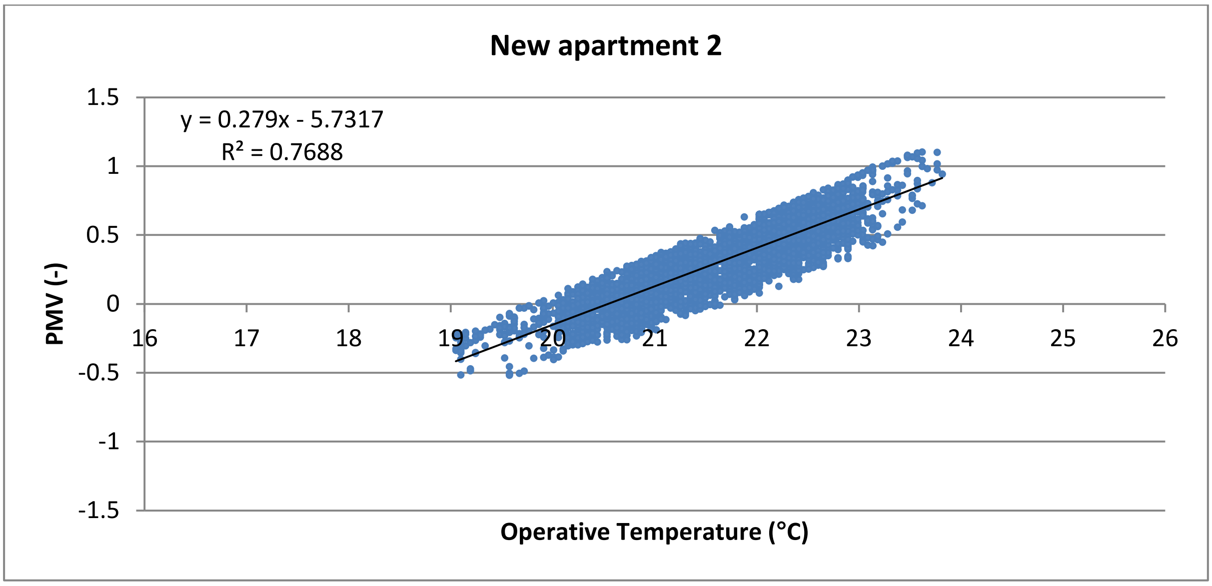
Old apartment 7: PMV= $0.2893T_{op} – 6.2998$, R^2= 0.7624

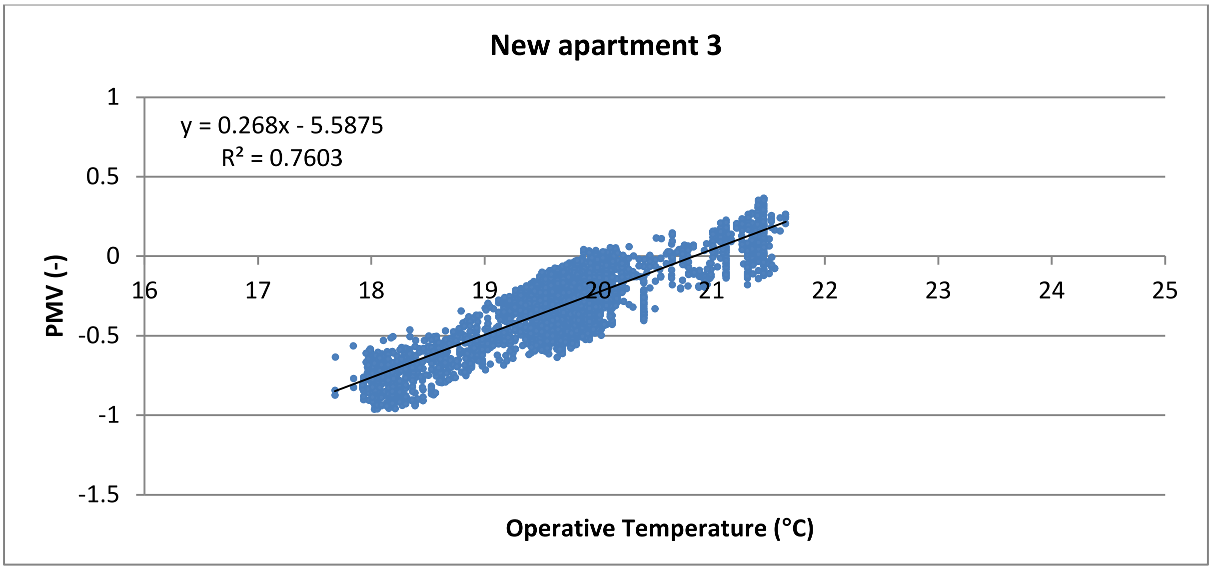
Where T_{op} is operative temperature, PMV is predicted mean votes. The equations were used to carry out the neutrality. The neutral operative temperature for PMV in old apartments were determined 21.7°C, 21.8°C, 21.6°C, 21.7°C, 21.8°C, 21.6°C and 21.8°C, respectively (when the Predicted mean vote = 0).

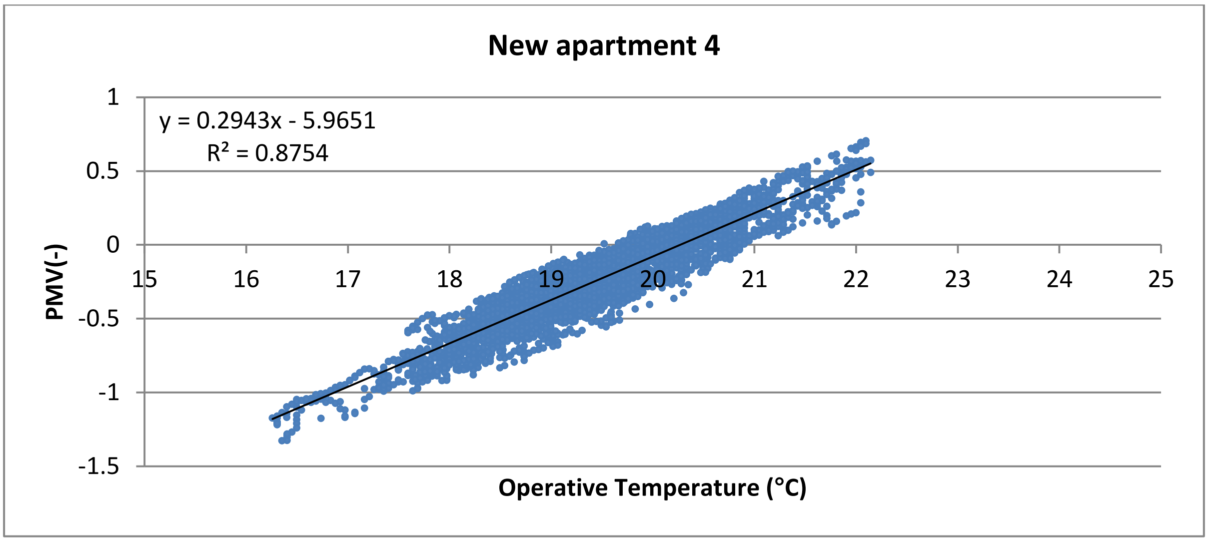
6.1.4.2 Predicted neutral temperature in new apartments during investigation periods

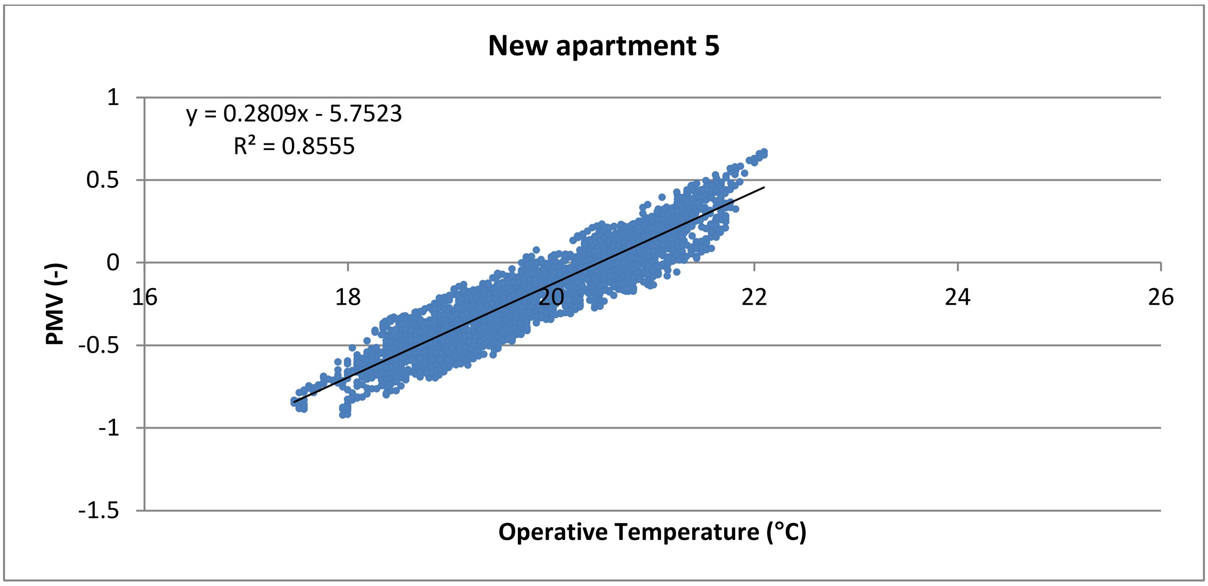
The mean indoor air temperature in new apartments is 20.7°C and the global temperature is 20.94°C, the mean Relative humidity obtained range from 48.3%, to 68.2% in the new apartments. The indoor air velocity in old apartments ranged from 0.03m/s–0.05m/s respectively in new apartments with a mean value of 0.056 m/s. According to interview survey in each apartment, the mean clothes insulation was identified as 0.9clo in new apartments. The metabolic rate was estimated as 1.1 met in each apartment in PMV model. As a consequence the calculated hourly PMV values in all old apartments during whole experimental period time can be worked out.

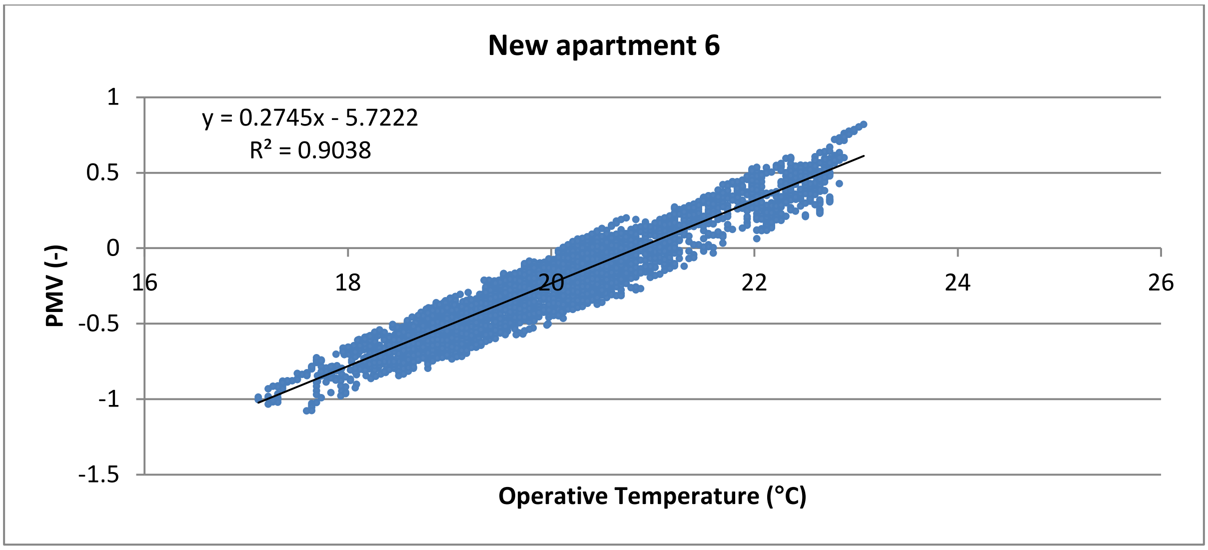





New apartment 3
y = 0.268x - 5.5875
R² = 0.7603
1
0.5
0
-0.5
-1
-1.5
PMV (-)
16
17
18
19
20
21
22
23
24
25
Operative Temperature (°C)


New apartment 4
y = 0.2943x - 5.9651
R² = 0.8754
1
0.5
0
-0.5
-1
-1.5
PMV(-)
15
16
17
18
19
20
21
22
23
24
25
Operative Temperature (°C)


New apartment 5
y = 0.2809x - 5.7523
R² = 0.8555
1
0.5
0
-0.5
-1
-1.5
PMV (-)
16
18
20
22
24
26
Operative Temperature (°C)



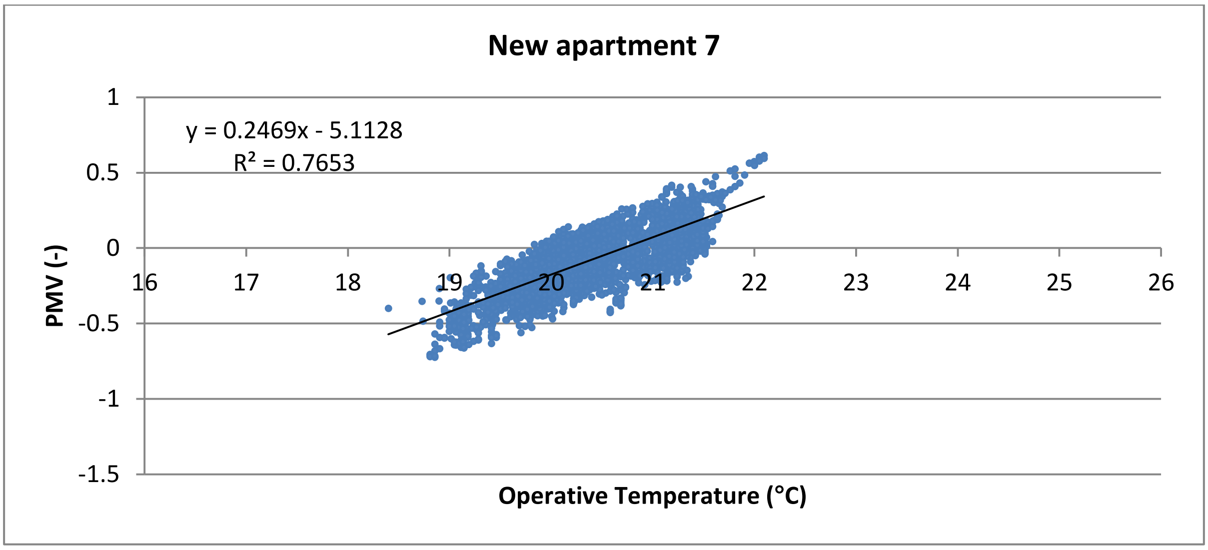


Figure 6.5 linear regressions of operative temperature and PMV values in all new apartments

Figure 6.5 shows that the PMV calculated according to Fanger's model plotted with operative temperature in each new apartment. The linear regression equation for each apartment that are

New apartment 1: PMV= $0.2726T_{op} - 5.6545$, $R^2 = 0.7895$

New apartment 2: PMV= $0.2790T_{op} - 5.7317$, $R^2 = 0.7688$

New apartment 3: PMV= $0.2680T_{op} - 5.5875$, $R^2 = 0.7603$

New apartment 4: PMV= $0.2809T_{op} - 5.9649$, $R^2= 0.8555$

New apartment 5: PMV= $0.2943T_{op} - 5.9651$, $R^2= 0.8754$

New apartment 6: PMV= $0.2745T_{op} - 5.7222$, $R^2= 0.8038$

New apartment 7: PMV= $0.2469T_{op} - 5.1128$, $R^2= 0.7653$

Where T_{op} is operative temperature, PMV is predicted mean votes. The neutrality value can be estimated by using above equations. The neutral operative temperature for PMV in new apartments were determined 20.7°C, 20.5°C, 20.8°C, 20.5°C, 20.2°C 20.8°C and 20.7°C, respectively (when the Predicted mean vote = 0). PMV value equal to zero regarded as a comfortable thermal environment. The neutral operative temperature of the occupants in new apartments is around 1.16°C lower than that of the occupants in old apartments.

6.1.5 Thermal preference

Figure 6.6 shows the thermal preference scale from occupants' survey, 57% occupants in old apartments want to change their indoor environment to be cooler, while 28% occupants do not want to change their environments. However, in new apartments, occupants provide higher acceptable of indoor environment, 42% occupants do not want to change their environments. One possible explanation being put forward was that there are control systems in new apartments, and occupants can control TRVs to change heating set-point in order to get their actual satisfied environments. However, occupants in old apartments only can open window when they not satisfied with their indoor climates. It is interesting to note that the similar findings were investigated from field study by Cao et al in Chinese residential buildings during winter period. It was found that the occupants in apartments with individual boiler heating respond higher acceptable evaluation than district heating without private control. This can be due to indoor environments were controlled by the users according to their actual demand in individual boiler heating apartments (Cao, et al., 2014). Behaviour adjustment likely to have strong impact on occupants' thermal sensation and preference presented above.

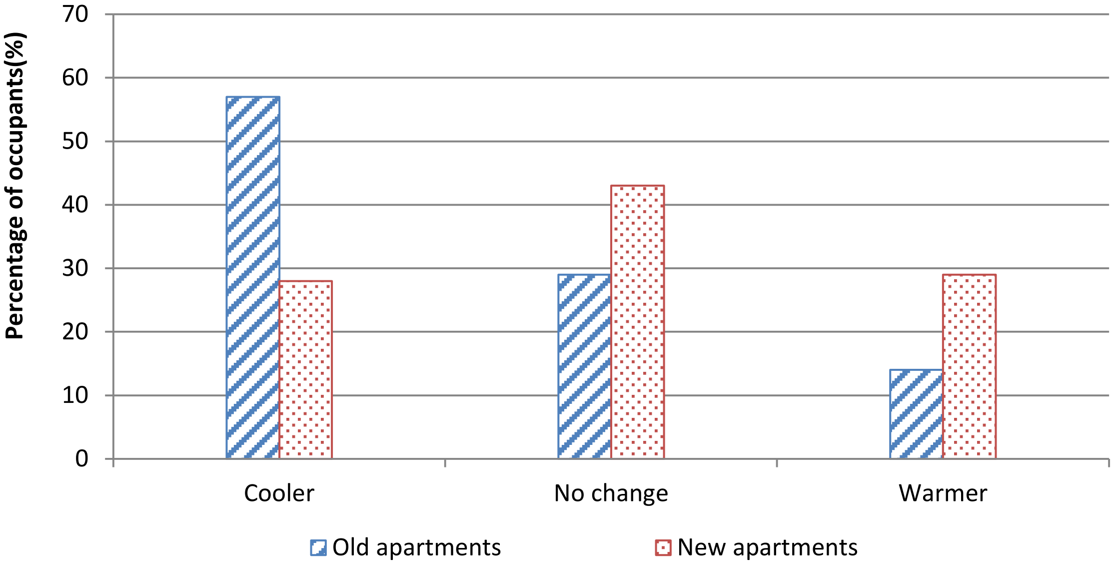


Figure 6.6 Distribution of thermal preference in new and old apartments

6.1.6 Indoor environment acceptability

Indoor environment acceptability votes reflect occupants' acceptability to the total environment (Wang, et al., 2011). Overall there are over 57% of satisfactions for thermal environment in the new apartments higher than that of 29% in old apartments. One possible explanation being put forward was that the indoor air temperature in old apartments higher than that in new ones, and occupants in old apartments prefer to have cooler indoor environment as well. Furthermore, it needs to take into account that the adaptive factors in new apartments should be considered into this field study.

In addition, gender influence thermal performance of AMV model and reflect that the personal factors are important to be considered. Gender differences on thermal comfort were investigated based on objective and subjective surveys in Chinese building during winter period, Lan et al. of laboratory experiments showed not only the male skin temperature is constantly higher than that of female but also the female is more sensitive to air temperature. Furthermore, females prefer warmer conditions than males (Lan, et al., 2008). According to interview survey, overall female occupants were more dissatisfied with indoor thermal environment than male occupants in either new or old apartments. In the phases of occupants were not satisfied with indoor environment, difference between females and males were more prominent than that in phase of satisfactions votes (Fig 6.7). From the results, overall, the 71% female and male occupants are satisfied to the thermal environment in old apartments. Generally, a comparative analysis of data collected from males and females in old apartments show a slightly disparity of thermal sensation between them. However, generally females have much higher complaint than males in both types of building. Comparing the female comfortable sensation, the higher numbers of females in old apartments feel uncomfortable than males in new ones.

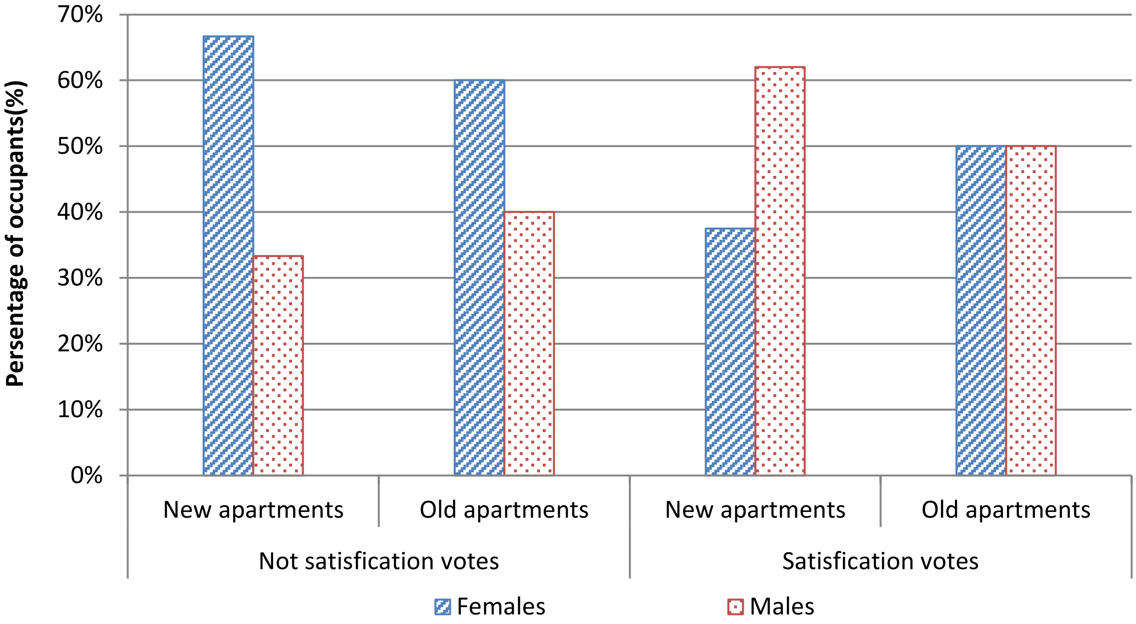


Figure 6.7 The percentage of satisfaction votes for male and female in old and new apartments

6.2 Summary

- The study investigated the correlations between PMV and AMV in both new and old apartments. In addition, thermal preference scales from occupants' survey show that 57% occupants in old apartments wanted their indoor environment to be cooler. Overall 57% of occupants reported to be satisfied with their thermal environment in the new apartments whilst only 29% of occupants reported to be thermally satisfied in the old apartments
- The mean neutral operative temperature for PMV in new apartments and old apartments were determined to be 20.6°C and 21.76°C, respectively (when

the Predicted mean vote = 0). PMV value equal to zero is regarded as a comfortable thermal environment. The neutral operative temperature of occupants in the new apartments is around 1.16°C lower than that of the occupants in old apartments.

7 Conclusion and future work

7.1 Research summary

Buildings account for 40% of total global energy consumption. Furthermore, the residential sector is one of the major global energy consumers (Ibn-Mohammed, et al., 2013; Laustsen, 2008). The building sector in China is one of the largest growing parts of energy use both at the construction stage and in the operational stage (Du, et al., 2004). Residential energy consumption is second largest energy use in China. The high residential energy use is due to huge waste in space heating in the Northern Central Heating Zone and as there are no heating control systems, the occupants can only open their windows to adjust indoor thermal conditions (Xu, et al., 2009; Chen, et al., 2011). In order to reduce building energy consumption, the Chinese government has revised the Chinese building design standard. Therefore, in 1995, the national standard on building energy efficiency in China (JGJ 26-95) was updated to become the new residential buildings standard (JGJ 26-2010) published in 2010. In the new standard, all residential buildings are highly recommended to install personal control on the heating system, such as by Thermostatic Radiator Valves (TRVs), together with ‘pay for what you use’ tariffs. Previous practice comprised of uncontrolled heating with payments based on floor area of the residence.

In the new guide the use of individual room temperature control and better insulation are highly recommended for new buildings. However, evidence of how the new standard can have an impact on the building energy consumption is not clear. In this research, the main aim was to explore the effect of recent Chinese government policy on the energy consumption in Chinese residential buildings. Literature review show that few researchers have focused on this area. Therefore, through the reviews of researches there are three potential factors impact on heating energy consumption. A reasonable number of buildings using each type of heating system were monitored. Energy consumption, occupant behaviour and thermal comfort were evaluated. Each potential factor was evaluated by using measurements and simulation in new and old case study residential buildings. The monitored data was used to validate the simulated model.

The literature review provided a thorough review of current state of energy consumption in buildings and especially in residential sector. In section 2.1 energy consumption of the building sector in the world and also the current status of the Chinese residential building sector is presented. Section 2.2 presented current legislation and code for buildings and it reviewed current status of energy conservation for residential building in China. In section 2.3, a review has conducted on the existing heating systems and reform of heating payment method in Chinese residential buildings. Section 2.4 presented occupant behaviour is one of important factor impact on energy consumption, furthermore, occupant behaviour related to heating energy consumption. The potential factors that influence on occupant window behaviour and heating behaviour were presented. Concept of thermal comfort in buildings related to energy consumption was discussed in section 2.5.1 to 2.5.2.

The methodology chapter introduced the experimental and simulation methods that were applied in this study. Seven apartments from an old and seven apartments from a new building were monitored from the 15th February to 14th March, 2014. The experimental methods were used to monitor the thermal environment, occupant behaviour and energy consumption and each household characteristic were defined using questionnaires survey. This was done to provide input parameters for the dynamic thermal modelling. In addition, simulation methods describe the detailed procedures that were chosen to validate the thermal modelling. Thereafter, the field study of thermal comfort was designed in old and new apartments.

The main findings of the experimental results from measurements in both new and old apartments were presented in this project. Further to this, all potential factors such as indoor thermal environment, occupant behaviour and thermal comfort related to heating energy consumption of new and old apartments were compared respectively.

- According to the results, the indoor temperature differences between old and new apartments were obvious. The observations indicate that the trend of indoor temperature is generally changed with outdoor temperature in both new and old apartments. The indoor temperatures in old apartments are generally higher than that in new apartments.

- The overall field measured data reflect that the windows in all old apartments were opened for 54% of the monitoring time, while they were opened only for 29% of the monitoring time in all new apartments. Generally, observed results reflect that indoor temperature increased from 15 to 20°C, the more windows opened obviously by occupants in old apartments. For all old apartments, the proportion of windows opening strongly related to indoor temperature in both living room and main bedroom. However, there was a slight increase in the probability as the indoor temperature increased in new apartments.
- From one week self-recording of heating behaviour and questionnaires. The results suggest that the use of TVRs by occupants for heating was related to outdoor temperatures in this study. Additionally, the finding show that age of dwellings, education level of occupants, energy price could be factors that impact the use of energy for heating.
- The results show that the new apartments consumed lower heating energy than the old apartments during the survey period and lead to an energy saving of 45%. The mean heating energy cost in new apartments is respectively 1106.4RMB less than the cost in old apartments.
- The difference heat loss between old and new apartments influence on energy consumption were determined. As a consequence, the reasonable air change rate corrected to 0.76ac/h in new apartments for calculation and corrected to 1.51ac/h in old apartments for calculation.
- The study investigated the correlations between PMV and AMV in both new and old apartments. In addition, thermal preference scales from occupants' survey show that 57% occupants in old apartments wanted their indoor environment to be cooler. Overall 57% of occupants reported to be satisfied with their thermal environment in the new apartments whilst only 29% of occupants reported to be thermally satisfied in the old apartments
- The mean neutral operative temperature for PMV in new apartments and old apartments were determined to be 20.6°C and 21.76°C, respectively (when the Predicted Mean Vote = 0). PMV value equal to zero is regarded as a comfortable thermal environment. The neutral operative temperature of occupants in the new apartments is around 1.16°C lower than that of the occupants in old apartments.

The measured energy consumption and simulated energy consumption were compared. The results show that acceptable level of validity between simulated and measured data. In particular, the analysis was focused on the effect of each factor on energy consumption and indoor thermal conditions were discussed.

- Generally, it was found that for all the apartments investigated in this study, the energy consumption predicted with simulation was lower than the measured data. To ensure the accurate of simulated results of energy consumption, the reasonable infiltration rate were input into modelling blocks.
- The simulation results indicated that better insulation levels made more substantial energy savings and the energy consumption was reduced by 28% after improved insulation level and building envelop. Energy consumption reduced by 12% after reduced heating set-point temperature. In addition, the simulation results confirmed that lower term of time of window opening can decrease heating energy consumption by 10%. It can be observed that for all old apartment model blocks, energy consumption reduced by 48.6% when combine all interventions in old apartment models.

The new buildings standard can reduce heating energy consumption and decrease heating cost. The mean heating energy cost in new apartments was found to be half of the cost in old apartments. After successful validation, effects of insulation level on energy consumption in old apartments were assessed by simulation. Generally, the simulation results indicated that the implication of upgrading insulation level is coherent with heating energy consumption.

7.2 Contribution of knowledge and guidelines

The main contribution of this work can be broken down into six categories:

- Previous studies do not pay much attention to evaluating the effects of new building standard on final energy consumption in new residential buildings compared with old residential buildings in China. In this study, each potential factors (insulation level, occupants' behaviour and thermal comfort) impact on heating energy consumption has been formally addressed and it was important for better understanding of new standards implementation in new residential buildings.

- Previous studies have not paid attention to occupants' thermal comfort and PMV model validity in different heating systems in residential buildings. However, in our research, this was done to identify the validity of PMV model in new and old apartments and the awareness of occupants regarding their thermal sensation.
- Previous studies focusing on occupants' window operation behaviour during wintertime in Chinese residential building are limited. In this study, the potential factors on window operation behaviour in new and old apartments are identified. The detailed results of occupant window operation behaviour in old apartments were compared with the results of occupant window operation behaviour in new apartments.
- Field study was carried out that investigated the central heating system with TRVs operated by occupants in new residential buildings together with new heating payment tariff. It found that there exists a difference in the frequency of occupant's adjustment of the TRVs set-point resulting in higher energy saving compared to old traditional heating strategy. However, there is a lack of research related to comparisons between old and new residential buildings in terms of influence factors such as indoor thermal environment, insulation level, thermal sensations, occupants' window behaviours and so on. This thesis has addressed all factors and potential influence on final heating behaviour during winter.
- The outcome of the study was based on data collected by monitoring of actual old and new residential buildings validated in simulation models. The results provide compelling evidence for government to adopt, refurbish and improve the insulation in old residential building. Our study confirmed and encouraged new standard implementation in new residential building to achieve the energy saving target.
- Recommendation to Chinese government: As recommended by the new standard, the new heating system with personal control and heat meter devices is highly recommended for new and refurbishment of old buildings.

This improvement can have a positive impact on the building energy consumption.

7.3 Limitations

Although in this research, the effect of new building standards on energy consumption in Chinese dwellings had been identified. There are some limitations in measurements and the limitations further related to simulation process:

- The measurement of window opening area: The equipment and devices were not monitored to the window opening area in all apartments due to the limitation of measurement.
- Hourly energy consumption: The hourly indoor air temperatures in all new and old apartments were monitored. In old apartments the energy consumption were recorded in-situ by spot measurements, as the installation of heat meter on each radiator was difficult.
- Heat loss of two buildings: air tightness and infiltration rates are important factors that impact the energy use of a building. During the experimental procedure, ventilation rate, the surface temperature of walls, heat losses of buildings were not recorded by monitoring in this study (see section 4.5).

7.4 Future works

- Extending the research in the investigation of window opening area in residential buildings. Previous studies have focused on the frequency of window opening in wintertime. Thus, this study can be extended in the investigation of window openings in summertime. The overall heat loss coefficient due to conductive heat losses can be investigated by using co-heating test in two types of buildings in future work.
- Utility companies and local government agencies can carry out activities aiming to educate the occupants on how to save energy (i.e. avoid unnecessarily high temperatures in apartment and reduce window opening in

order to achieve lower indoor temperature. Use heating control system (i.e. TRVs) to achieve lower indoor temperature and also turn down the TRVs for unoccupied hours in rooms.

- A smart radiator thermostat can be considered to be installed in radiators which can be turned down using smart phones when no one is home and start to pre-heat before they arrive to home.

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Appendix A

Table A-0.1:The reasons for window opening

Can you please fill out the form and choose the reason why you open windows normally? Please use “✓” to mark it into table.

Apartment No: (   )

	Reason 1	**Reason 2**	**Reason 3**
Answers	Get lower indoor climate	Get fresh air	Remove moisture
Yes			
No			
I don't know			

Appendix B

This appendix present the questionnaires of was distributed to each household, asking them to self-record their heating behaviour (i.e. adjustment of the TRV settings) over a whole week period. The occupants were asked for filling out the self-questionnaires, as for instance, when they turn off/turn on the TRVs need to mark in questionnaire. And also when they adjust TRVs set-point, the range and time need to be marked.

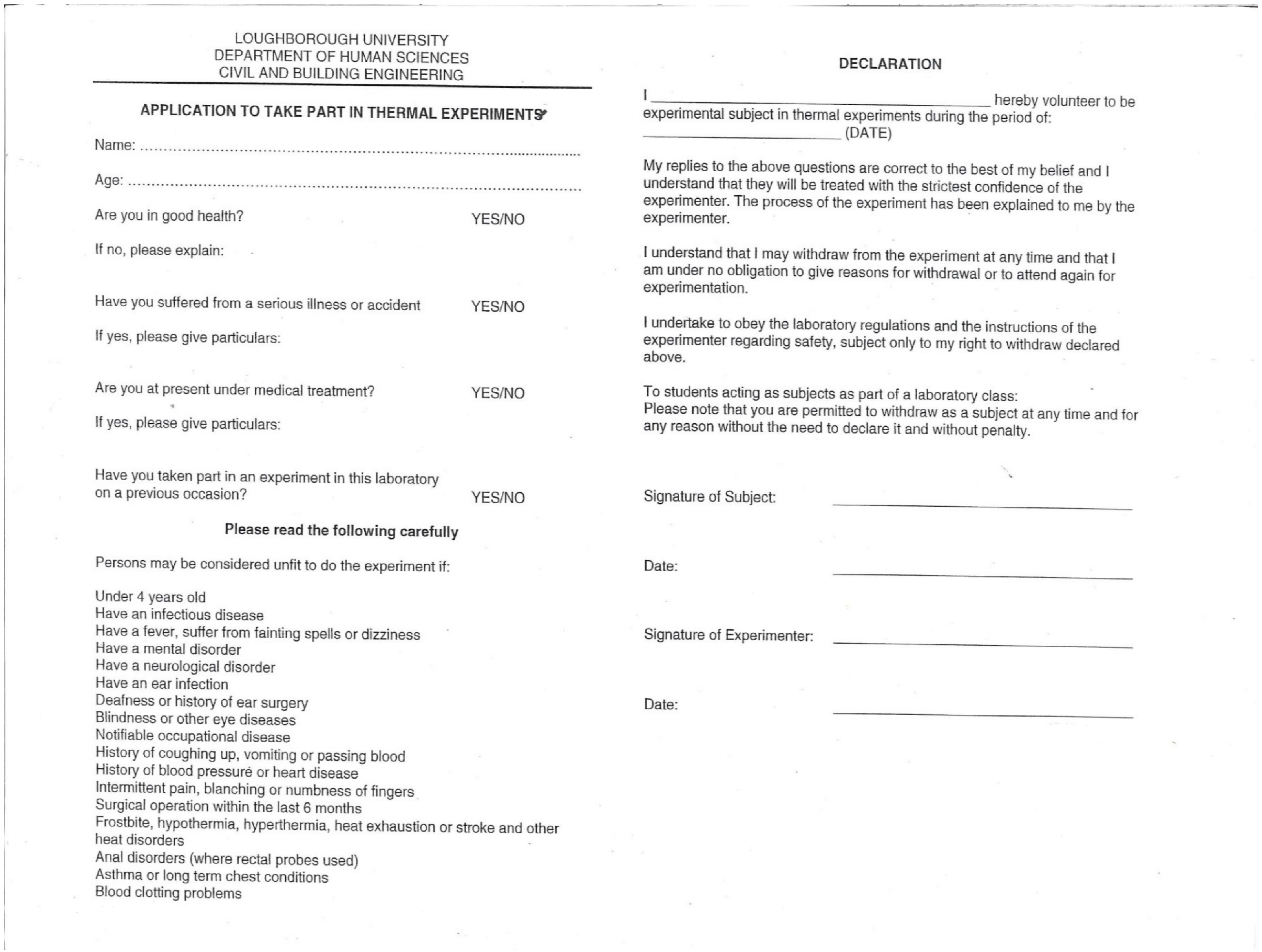
Table B-0.1:Heating set-point (TRVs) adjustment questionnaires for new apartments

Please record TRVs set-point based on adjustment.

1) The original heating set-point of TRVs is:

2) The details of questionnaire can be seen below:

	Day 1		**Day 2**		**Day 3**		**Day 4**		**Day 5**		**Day 6**		**Day 7**	
Range of set-point	Time	Whether adjust (Yes/No)	Time	Whether adjust (Yes/No)	Time	Whether adjust (Yes/No)	Time	Whether adjust (Yes/No)	Time	Whether adjust (Yes/No)	Time	Whether adjust (Yes/No)	Time	Whether adjust (Yes/No)
5														
4														
3														
2														
1														
(Off) 0														



LOUGHBOROUGH UNIVERSITY
DEPARTMENT OF HUMAN SCIENCES
CIVIL AND BUILDING ENGINEERING

APPLICATION TO TAKE PART IN THERMAL EXPERIMENTS

Name: ....

Age: ....

Are you in good health? YES/NO

If no, please explain:

Have you suffered from a serious illness or accident YES/NO

If yes, please give particulars:

Are you at present under medical treatment? YES/NO

If yes, please give particulars:

Have you taken part in an experiment in this laboratory on a previous occasion? YES/NO

Please read the following carefully

Persons may be considered unfit to do the experiment if:

Under 4 years old
Have an infectious disease
Have a fever, suffer from fainting spells or dizziness
Have a mental disorder
Have a neurological disorder
Have an ear infection
Deafness or history of ear surgery
Blindness or other eye diseases
Notifiable occupational disease
History of coughing up, vomiting or passing blood
History of blood pressure or heart disease
Intermittent pain, blanching or numbness of fingers
Surgical operation within the last 6 months
Frostbite, hypothermia, hyperthermia, heat exhaustion or stroke and other heat disorders
Anal disorders (where rectal probes used)
Asthma or long term chest conditions
Blood clotting problems

DECLARATION

I ________________________________ hereby volunteer to be experimental subject in thermal experiments during the period of:
____________________ (DATE)

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence of the experimenter. The process of the experiment has been explained to me by the experimenter.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, subject only to my right to withdraw declared above.

To students acting as subjects as part of a laboratory class:
Please note that you are permitted to withdraw as a subject at any time and for any reason without the need to declare it and without penalty.

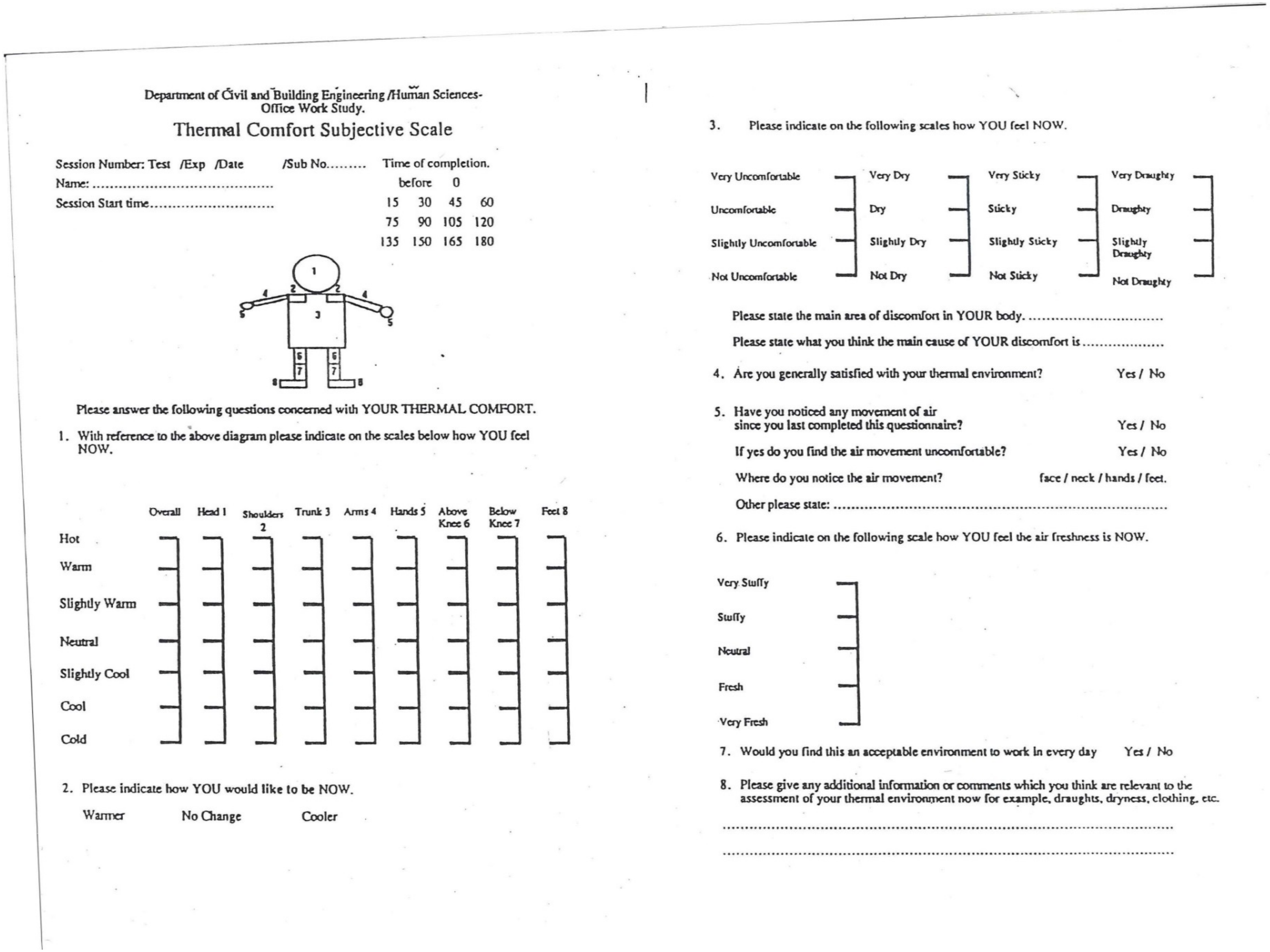
Signature of Subject: ____________________

Date: ____________________

Signature of Experimenter: ____________________

Date: ____________________

Table B-0.2:The questionnaires of thermal sensation



Department of Civil and Building Engineering /Human Sciences-
Office Work Study.

Thermal Comfort Subjective Scale

Session Number: Test /Exp /Date /Sub No.........
Name: ....
Session Start time............................

Time of completion.
before 0
15 30 45 60
75 90 105 120
135 150 165 180

Please answer the following questions concerned with YOUR THERMAL COMFORT.

1. With reference to the above diagram please indicate on the scales below how YOU feel NOW.

	Overall	Head 1	Shoulders 2	Trunk 3	Arms 4	Hands 5	Above Knee 6	Below Knee 7	Feet 8
Hot									
Warm									
Slightly Warm									
Neutral									
Slightly Cool									
Cool									
Cold									

2. Please indicate how YOU would like to be NOW.

Warmer No Change Cooler

3. Please indicate on the following scales how YOU feel NOW.

Very Uncomfortable	Very Dry	Very Sticky	Very Draughty
Uncomfortable	Dry	Sticky	Draughty
Slightly Uncomfortable	Slightly Dry	Slightly Sticky	Slightly Draughty
Not Uncomfortable	Not Dry	Not Sticky	Not Draughty

Please state the main area of discomfort in YOUR body. ....

Please state what you think the main cause of YOUR discomfort is ....

4. Are you generally satisfied with your thermal environment? Yes / No

5. Have you noticed any movement of air since you last completed this questionnaire? Yes / No

If yes do you find the air movement uncomfortable? Yes / No

Where do you notice the air movement? face / neck / hands / feet.

Other please state: ....

6. Please indicate on the following scale how YOU feel the air freshness is NOW.

Very Stuffy
Stuffy
Neutral
Fresh
Very Fresh

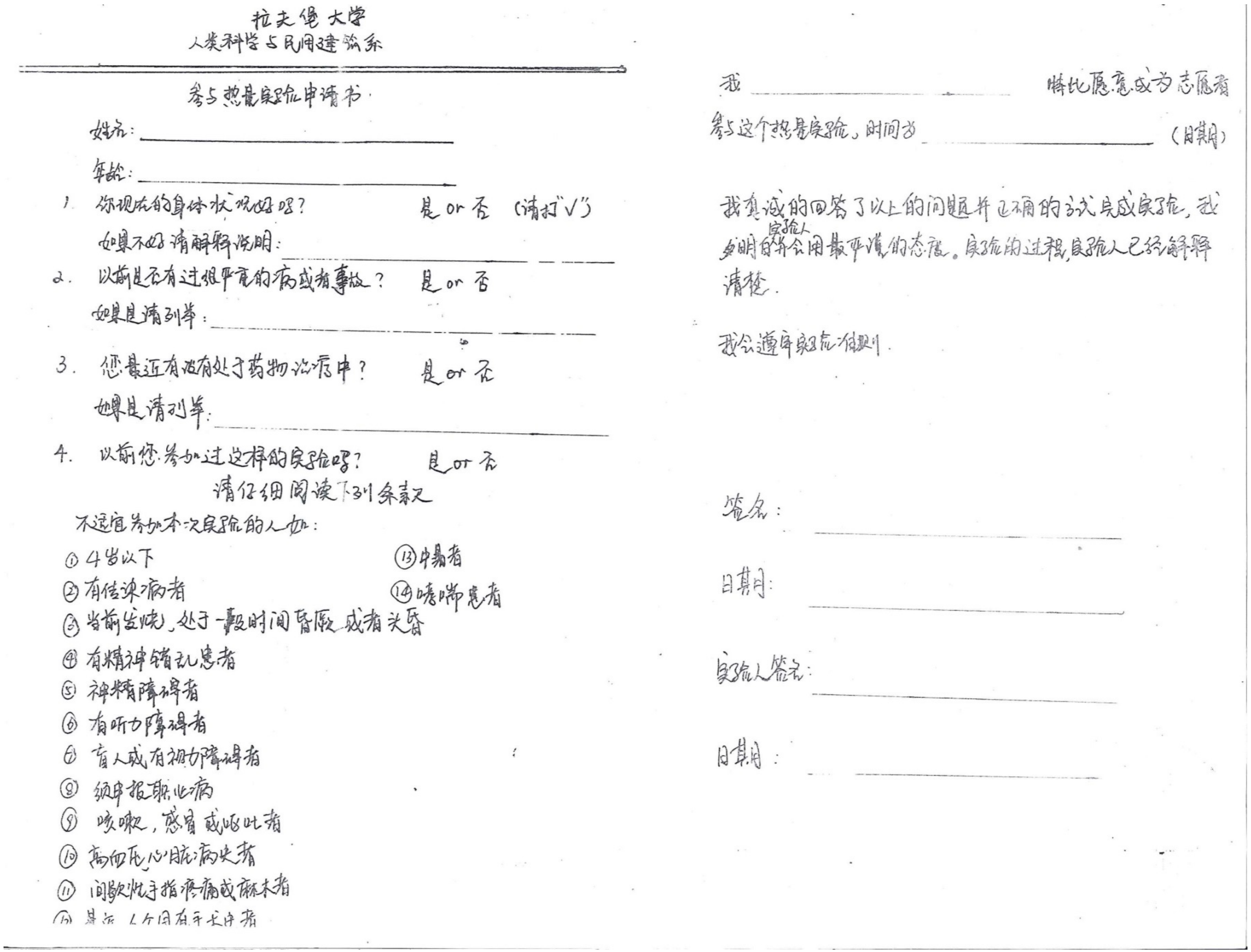
7. Would you find this an acceptable environment to work in every day Yes / No

8. Please give any additional information or comments which you think are relevant to the assessment of your thermal environment now for example, draughts, dryness, clothing, etc.

....

....

Table B-0.3:The details of questionnaires of thermal comfort study



拉夫堡大学
人类科学与民用建筑系

参与热量实验申请书

姓名：

年龄：

1. 你现在的身体状况好吗？ 是 or 否 （请打"√"）
如果不好请解释说明：
2. 以前是否有过很严重的病或者事故？ 是 or 否
如果是请列举：
3. 您最近有没有处于药物治疗中？ 是 or 否
如果是请列举：
4. 以前您参加过这样的实验吗？ 是 or 否

请仔细阅读下列条款

不适宜参加本次实验的人如：

① 4岁以下
② 有传染病者
③ 当前发烧、处于一段时间昏厥或者头昏
④ 有精神错乱患者
⑤ 神精障碍者
⑥ 有听力障碍者
⑦ 盲人或有视力障碍者
⑧ 须申报职业病
⑨ 咳嗽，感冒或呕吐者
⑩ 高血压、心脏病史者
⑪ 间歇性手指疼痛或麻木者
⑫ 最近 六个月有手术史者
⑬ 中暑者
⑭ 哮喘患者

我 ____ 特此愿意成为志愿者
参与这个热量实验，时间为 ____ （日期）

我真诚的回答了以上的问题并正确的方式完成实验，我声明自实验人并会用最平淡的态度。实验的过程，实验人已经解释清楚。

我会遵守实验准则。

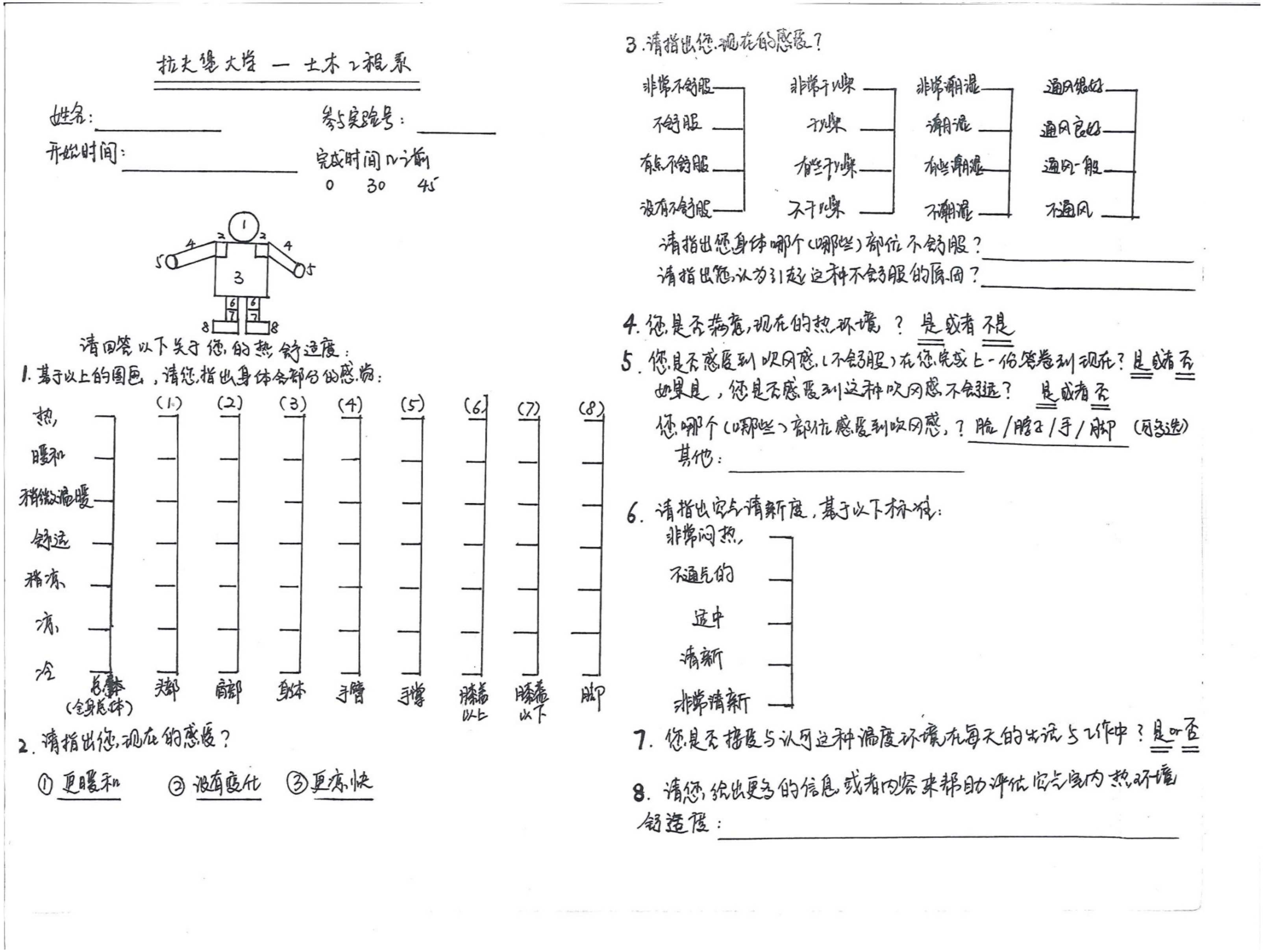
签名：

日期：

实验人签名：

日期：

TableB-0.4: The questionnaires of thermal sensation(in Chinese)



拉夫堡大学 — 土木工程系

姓名：________ 参与实验号：________

开始时间：________ 完成时间以分钟 0 30 45

请回答以下关于您的热舒适度：

1. 基于以上的图画，请您指出身体各部分的感觉：

	总体（全身总体）	(1) 头部	(2) 肩部	(3) 身体	(4) 手臂	(5) 手掌	(6) 膝盖以上	(7) 膝盖以下	(8) 脚
热									
暖和									
稍微偏暖									
舒适									
稍凉									
凉									
冷									

2. 请指出您现在的感受？

① 更暖和 ② 没有变化 ③ 更凉快

3. 请指出您现在的感受？

非常不舒服	非常干燥	非常潮湿	通风很好
不舒服	干燥	潮湿	通风良好
有点不舒服	有些干燥	有些潮湿	通风一般
没有不舒服	不干燥	不潮湿	不通风

请指出您身体哪个（哪些）部位不舒服？________

请指出您认为引起这种不舒服的原因？________

4. 您是否满意现在的热环境？ 是或者 不是

5. 您是否感受到吹风感（不舒服）在您完成上一份答卷到现在？是或者否

如果是，您是否感受到这种吹风感不舒适？ 是或者否

您哪个（哪些）部位感受到吹风感？ 脸 / 脖子 / 手 / 脚 （可多选）

其他：________

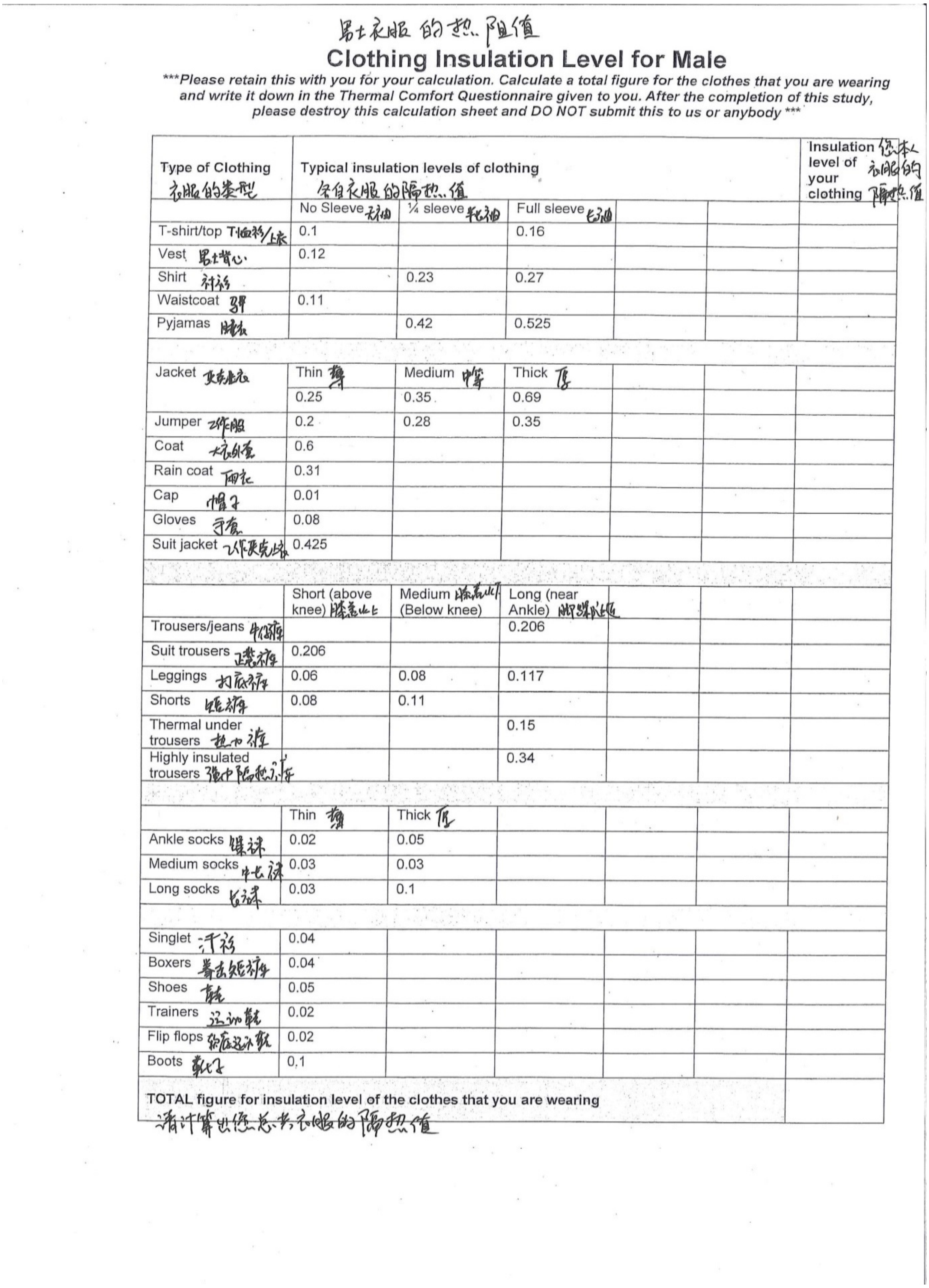
6. 请指出空气清新度，基于以下标准：

- 非常闷热
- 不通气的
- 适中
- 清新
- 非常清新

7. 您是否接受与认可这种温度环境在每天的生活与工作中？是或否

8. 请您给出更多的信息或者内容来帮助评估室内热环境舒适度：________

Table B-0.5: The form of clothes insulation level of male



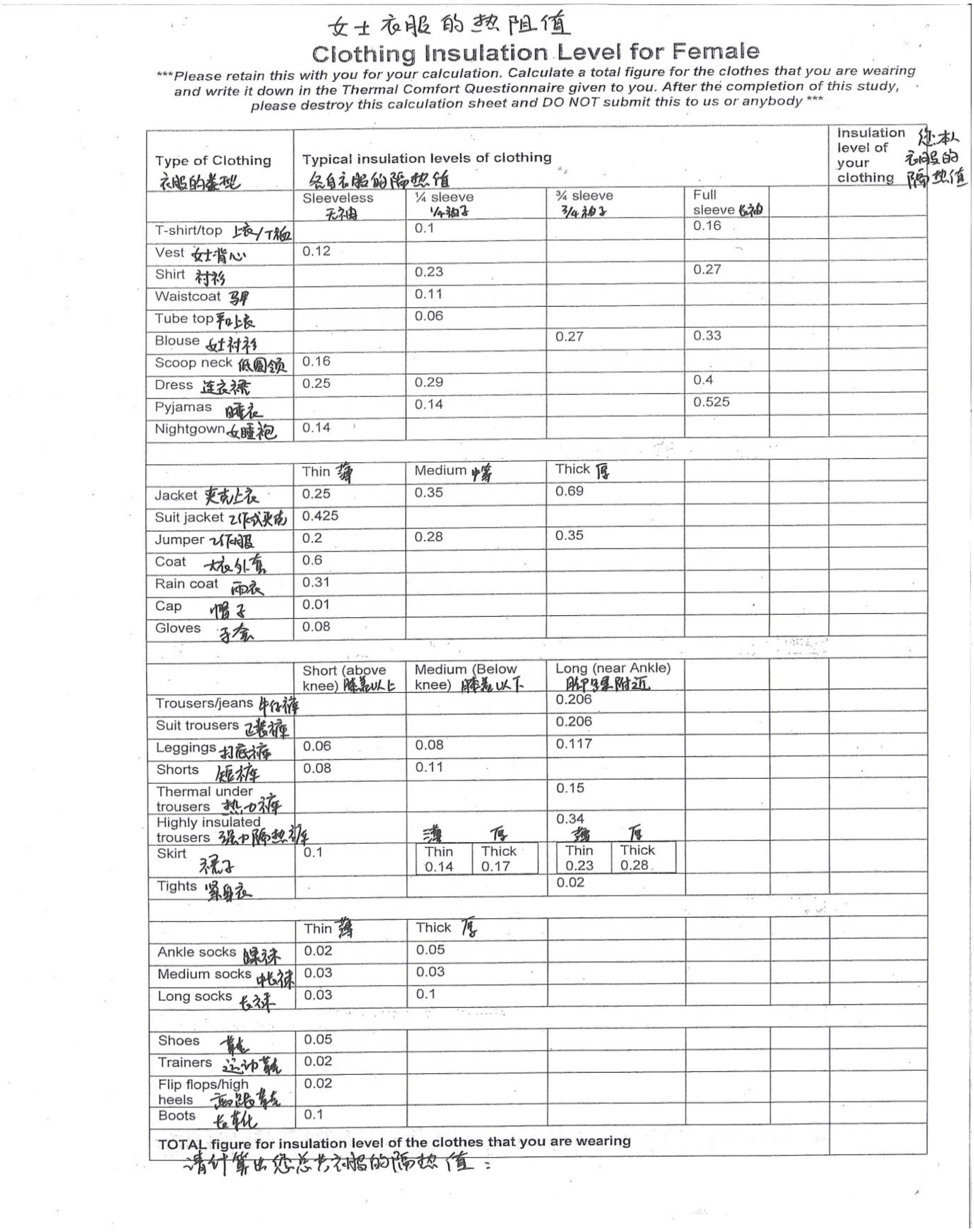
男士衣服的热阻值

Clothing Insulation Level for Male

****Please retain this with you for your calculation. Calculate a total figure for the clothes that you are wearing and write it down in the Thermal Comfort Questionnaire given to you. After the completion of this study, please destroy this calculation sheet and DO NOT submit this to us or anybody ****

Type of Clothing 衣服的类型	**Typical insulation levels of clothing** 各自衣服的隔热值					**Insulation level of your clothing** 您本人衣服的隔热值
	No Sleeve 无袖	¼ sleeve 半长袖	Full sleeve 长袖			
T-shirt/top T恤衫/上衣	0.1		0.16			
Vest 男士背心	0.12					
Shirt 衬衫		0.23	0.27			
Waistcoat 马甲	0.11					
Pyjamas 睡衣		0.42	0.525			
Jacket 夹克外衣	Thin 薄	Medium 中等	Thick 厚			
	0.25	0.35	0.69			
Jumper 工作服	0.2	0.28	0.35			
Coat 大衣外套	0.6					
Rain coat 雨衣	0.31					
Cap 帽子	0.01					
Gloves 手套	0.08					
Suit jacket 工作夹克上衣	0.425					
	Short (above knee) 膝盖以上	Medium 膝盖以下 (Below knee)	Long (near Ankle) 脚踝以上			
Trousers/jeans 牛仔裤			0.206			
Suit trousers 正装裤	0.206					
Leggings 打底裤	0.06	0.08	0.117			
Shorts 短裤	0.08	0.11				
Thermal under trousers 热内裤			0.15			
Highly insulated trousers 强力隔热衣裤			0.34			
	Thin 薄	Thick 厚				
Ankle socks 踝袜	0.02	0.05				
Medium socks 中长袜	0.03	0.03				
Long socks 长袜	0.03	0.1				
Singlet 汗衫	0.04					
Boxers 拳击短裤	0.04					
Shoes 鞋	0.05					
Trainers 运动鞋	0.02					
Flip flops 软底运动鞋	0.02					
Boots 靴子	0.1					
TOTAL figure for insulation level of the clothes that you are wearing 请计算出您总共衣服的隔热值						

Table B-0.6:The form of clothes insulation level for males



女士衣服的热阻值

Clothing Insulation Level for Female

****Please retain this with you for your calculation. Calculate a total figure for the clothes that you are wearing and write it down in the Thermal Comfort Questionnaire given to you. After the completion of this study, please destroy this calculation sheet and DO NOT submit this to us or anybody ****

Type of Clothing 衣服的类型	Typical insulation levels of clothing 各自衣服的隔热值					Insulation level of your clothing 您本人衣服的隔热值
	Sleeveless 无袖	¼ sleeve 1/4袖子	¾ sleeve 3/4袖子	Full sleeve 长袖		
T-shirt/top 上衣/T恤		0.1		0.16		
Vest 女士背心	0.12					
Shirt 衬衫		0.23		0.27		
Waistcoat 马甲		0.11				
Tube top 平口上衣		0.06				
Blouse 女士衬衫			0.27	0.33		
Scoop neck 低圆领	0.16					
Dress 连衣裙	0.25	0.29		0.4		
Pyjamas 睡衣		0.14		0.525		
Nightgown 女睡袍	0.14					
	Thin 薄	Medium 中等	Thick 厚			
Jacket 夹克上衣	0.25	0.35	0.69			
Suit jacket 工作式夹克	0.425					
Jumper 工作服	0.2	0.28	0.35			
Coat 大衣外套	0.6					
Rain coat 雨衣	0.31					
Cap 帽子	0.01					
Gloves 手套	0.08					
	Short (above knee) 膝盖以上	Medium (Below knee) 膝盖以下	Long (near Ankle) 脚踝附近			
Trousers/jeans 牛仔裤			0.206			
Suit trousers 工装裤			0.206			
Leggings 打底裤	0.06	0.08	0.117			
Shorts 短裤	0.08	0.11				
Thermal under trousers 热力裤			0.15			
Highly insulated trousers 强力隔热裤			0.34			
Skirt 裙子	0.1	薄 Thin 0.14 厚 Thick 0.17	薄 Thin 0.23 厚 Thick 0.28			
Tights 紧身衣			0.02			
	Thin 薄	Thick 厚				
Ankle socks 踝袜	0.02	0.05				
Medium socks 中长袜	0.03	0.03				
Long socks 长袜	0.03	0.1				
Shoes 鞋	0.05					
Trainers 运动鞋	0.02					
Flip flops/high heels 高跟鞋	0.02					
Boots 长靴	0.1					
TOTAL figure for insulation level of the clothes that you are wearing						

请计算出您总共衣服的隔热值：

TableB-0.7: The form of clothes insulation level for females

Appendix C

Old apartment 1

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	4.8	2.8	13.44
	Wall2	3.1	2.8	8.68
	Wall3(exclude window)	4.8	2.8	13.44
	Wall4	3.1	2.8	6.0456
Dimension for floor area		4.8	3.1	14.88
Dimension for roof area		4.8	3.1	14.88
Volume of room		4.8*3.1*2.8m		41.664

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	4.2	2.8	11.76
	Wall2	3.1	2.8	8.68
	Wall3	4.2	2.8	11.76
	Wall4(exclude window)	3.1	2.8	6.0456
Dimension for floor area		4.2	3.1	13.02
Dimension for roof area		4.2	3.1	13.02
Volume of room		4.2*3.1*2.8m		36.456

Old apartment 2

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	4.8	2.8	13.44
	Wall2	3.1	2.8	8.68
	Wall3(exclude window)	4.8	2.8	10.8056
	Wall4	3.1	2.8	8.68
Dimension for floor area		4.8	3.1	14.88
Dimension for roof area		4.8	3.1	14.88
Volume of room		4.8*3.1*2.8m		41.664

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	4.2	2.8	11.76
	Wall2	3.1	2.8	8.68
	Wall3	4.2	2.8	11.76
	Wall4(exclude window)	3.1	2.8	6.0456
Dimension for floor area		4.2	3.1	13.02
Dimension for roof area		4.2	3.1	13.02
Volume of room		4.2*3.1*2.8m		36.456

Old apartment 3

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	5.1	2.8	14.28
	Wall2	3.4	2.8	9.52
	Wall3(exclude window)	5.1	2.8	11.6456
	Wall4	3.4	2.8	9.52
Dimension for floor area		5.1	3.4	17.34
Dimension for roof area		5.1	3.4	17.34
Volume of room		5.1*3.4*2.8m		48.552

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	4.5	2.8	12.6
	Wall2	4	2.8	11.2
	Wall3(exclude window)	4.5	2.8	8.82
	Wall4	4	2.8	11.2
Dimension for floor area		4.5	4	18
Dimension for roof area		4.5	4	18
Volume of room		4.5*4*2.8m		50.4

Old apartment 4

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	5.1	2.8	14.28
	Wall2	3.4	2.8	9.52
	Wall3(exclude window)	5.1	2.8	11.6456
	Wall4	3.4	2.8	9.52
Dimension for floor area		5.1	3.4	17.34
Dimension for roof area		5.1	3.4	17.34
Volume of room		5.1*3.4*2.8m		48.552

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	4.5	2.8	12.6
	Wall2	4	2.8	11.2
	Wall3(exclude window)	4.5	2.8	8.82
	Wall4	4	2.8	11.2
Dimension for floor area		4.5	4	18
Dimension for roof area		4.5	4	18
Volume of room		4.5*4*2.8m		50.4

Old apartment 5

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	4.8	2.8	13.44
	Wall2	3.1	2.8	8.68
	Wall3(exclude window)	4.8	2.8	10.8056
	Wall4	3.1	2.8	8.68
Dimension for floor area		4.8	3.1	14.88
Dimension for roof area		4.8	3.1	14.88
Volume of room		4.8*3.1*2.8m		41.664

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	4.2	2.8	11.76
	Wall2	3.1	2.8	8.68
	Wall3	4.2	2.8	11.76
	Wall4(exclude window)	3.1	2.8	6.0456
Dimension for floor area		4.2	3.1	13.02
Dimension for roof area		4.2	3.1	13.02
Volume of room		4.2*3.1*2.8m		36.456

Old apartment 6

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	5.1	2.8	14.28
	Wall2	3.4	2.8	9.52
	Wall3(exclude window)	5.1	2.8	11.6456
	Wall4	3.4	2.8	9.52
Dimension for floor area		5.1	3.4	17.34
Dimension for roof area		5.1	3.4	17.34
Volume of room		5.1*3.4*2.8m		48.552

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	4.5	2.8	12.6
	Wall2	4	2.8	11.2
	Wall3(exclude window)	4.5	2.8	8.82
	Wall4	4	2.8	11.2
Dimension for floor area		4.5	4	18
Dimension for roof area		4.5	4	18
Volume of room		4.5*4*2.8m		50.4

Old apartment 7

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.78	1.48	2.6344
Dimension for wall area	Wall1	5.2	2.8	14.56
	Wall2	4.5	2.8	12.6
	Wall3(exclude window)	5.2	2.8	11.9256
	Wall4	4.5	2.8	12.6
Dimension for floor area		5.2	4.5	23.4
Dimension for roof area		5.2	4.5	23.4
Volume of room		5.2*4.5*2.8m		65.52

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	4.6	2.8	12.88
	Wall2	4.3	2.8	12.04
	Wall3(exclude window)	4.6	2.8	9.1
	Wall4	4.3	2.8	12.04
Dimension for floor area		4.6	4.3	19.78
Dimension for roof area		4.6	4.3	19.78
Volume of room		4.6*4.3*2.8m		55.384

New apartment 1

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.2	2.8	14.56
	Wall2	3.6	2.8	10.08
	Wall3(exclude window)	5.2	2.8	10.78
	Wall4	3.6	2.8	10.08
Dimension for floor area		5.2	3.6	18.72
Dimension for roof area		5.2	3.6	18.72
Volume of room		5.2*3.6*2.8m		53.424

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	4.3	2.8	12.04
	Wall2	3.5	2.8	9.8
	Wall3	4.3	2.8	12.04
	Wall4(exclude window)	3.5	2.8	7.1
Dimension for floor area		4.3	3.5	15.05
Dimension for roof area		4.3	3.5	15.05
Volume of room		4.3*3.5*2.8m		42.14

New apartment 2

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.3	2.8	14.84
	Wall2	3.6	2.8	10.08
	Wall3(exclude window)	5.3	2.8	11.06
	Wall4	3.6	2.8	10.08
Dimension for floor area		5.3	3.6	19.08
Dimension for roof area		5.3	3.6	19.08
Volume of room		5.3*3.6*2.8m		53.424

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	4.5	2.8	12.6
	Wall2	3.6	2.8	10.08
	Wall3	4.5	2.8	12.6
	Wall4(exclude window)	3.6	2.8	7.38
Dimension for floor area		4.5	3.6	16.2
Dimension for roof area		4.5	3.6	16.2
Volume of room		4.5*3.6*2.8m		45.36

New apartment 3

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.1	2.8	14.28
	Wall2	3.8	2.8	10.64
	Wall3(exclude window)	5.1	2.8	10.5
	Wall4	3.8	2.8	10.64
Dimension for floor area		5.1	3.8	19.38
Dimension for roof area		5.1	3.8	19.38
Volume of room		5.1*3.8*2.8m		54.264

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	3.8	2.8	10.64
	Wall2	4	2.8	11.2
	Wall3	3.8	2.8	10.64
	Wall4(exclude window)	4	2.8	8.5
Dimension for floor area		4	3.8	15.2
Dimension for roof area		4	3.8	15.2
Volume of room		4*3.8*2.8m		42.56

New apartment 4

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.1	2.8	14.28
	Wall2	3.8	2.8	10.64
	Wall3(exclude window)	5.1	2.8	10.5
	Wall4	3.8	2.8	10.64
Dimension for floor area		5.1	3.8	19.38
Dimension for roof area		5.1	3.8	19.38
Volume of room		5.1*3.8*2.8m		54.264

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	3.8	2.8	10.64
	Wall2	4	2.8	11.2
	Wall3	3.8	2.8	10.64
	Wall4(exclude window)	4	2.8	8.5
Dimension for floor area		4	3.8	15.2
Dimension for roof area		4	3.8	15.2
Volume of room		4*3.8*2.8m		42.56

New apartment 5

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.3	2.8	14.84
	Wall2	3.6	2.8	10.08
	Wall3(exclude window)	5.3	2.8	11.06
	Wall4	3.6	2.8	10.08
Dimension for floor area		5.3	3.6	19.08
Dimension for roof area		5.3	3.6	19.08
Volume of room		5.3*3.6*2.8m		53.424

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	4.5	2.8	12.6
	Wall2	3.6	2.8	10.08
	Wall3	4.5	2.8	12.6
	Wall4(exclude window)	3.6	2.8	7.38
Dimension for floor area		4.5	3.6	16.2
Dimension for roof area		4.5	3.6	16.2
Volume of room		4.5*3.6*2.8m		45.36

New apartment 6

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.1	2.8	14.28
	Wall2	3.8	2.8	10.64
	Wall3(exclude window)	5.1	2.8	10.5
	Wall4	3.8	2.8	10.64
Dimension for floor area		5.1	3.8	19.38
Dimension for roof area		5.1	3.8	19.38
Volume of room		5.1*3.8*2.8m		54.264

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	3.8	2.8	10.64
	Wall2	4	2.8	11.2
	Wall3	3.8	2.8	10.64
	Wall4(exclude window)	4	2.8	8.5
Dimension for floor area		4	3.8	15.2
Dimension for roof area		4	3.8	15.2
Volume of room		4*3.8*2.8m		42.56

New apartment 7

Living Room

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	2.1	3.78
Dimension for wall area	Wall1	5.2	2.8	14.56
	Wall2	3.6	2.8	10.08
	Wall3(exclude window)	5.2	2.8	10.78
	Wall4	3.6	2.8	10.08
Dimension for floor area		5.2	3.6	18.72
Dimension for roof area		5.2	3.6	18.72
Volume of room		5.2*3.6*2.8m		53.424

Bedroom

		Height(m)	Width(m)	Sum areas(m^2)
Dimension for window area		1.8	1.5	2.7
Dimension for wall area	Wall1	4.3	2.8	12.04
	Wall2	3.5	2.8	9.8
	Wall3	4.3	2.8	12.04
	Wall4(exclude window)	3.5	2.8	7.1
Dimension for floor area		4.3	3.5	15.05
Dimension for roof area		4.3	3.5	15.05
Volume of room		4.3*3.5*2.8m		42.14

Appendix D

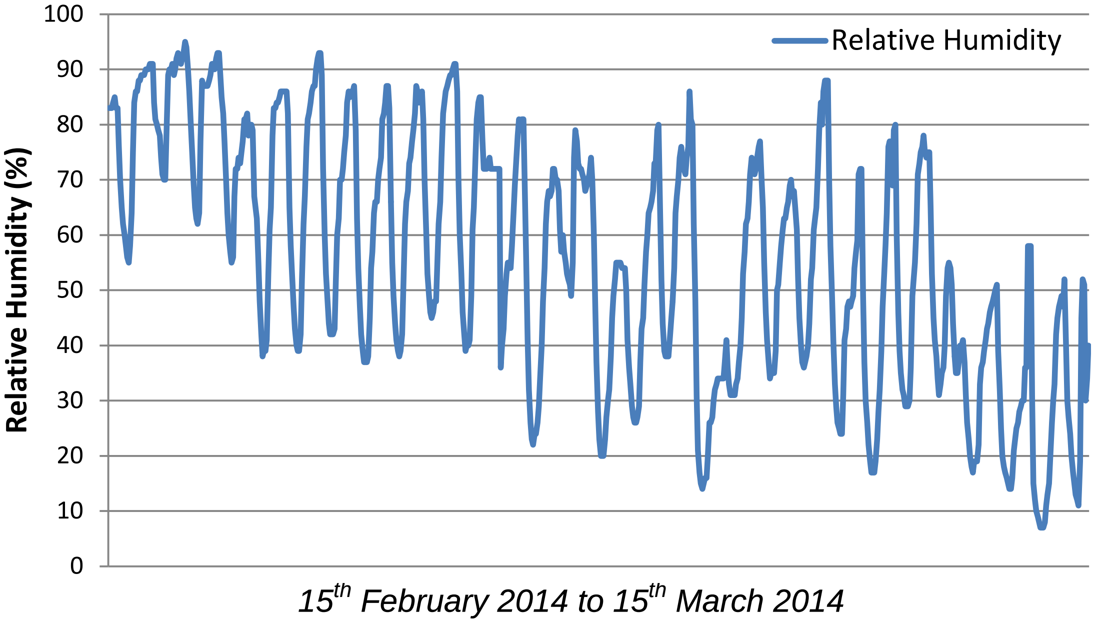


Figure D-0.1 Hourly Relative Humidity plot for period 15th February 2014 to 15th March 2014

Appendix E

To identify the U-value, firstly R-value of the layers that make up the structure must be worked out. The approach can be described using the following equation:

$$\mathbf{R} = \frac{\mathbf{d}}{\boldsymbol{\lambda}} \tag{14}$$

Where

d is the thickness of the material (mm)

λ is the thermal conductivity of the material (W/m °C)

The U-value can be determined as following equation

$$\mathbf{U} = \frac{\mathbf{1}}{\sum \mathbf{R}} \tag{15}$$

Then

$$\sum \mathbf{R} = \mathbf{R_{si}} + \mathbf{R_1} + \mathbf{R_2} + \cdots + \mathbf{R_n} + \mathbf{R_{se}} \tag{16}$$

Where

R_{si} is the resistivity of a "boundary layer" of air on the inside surface.

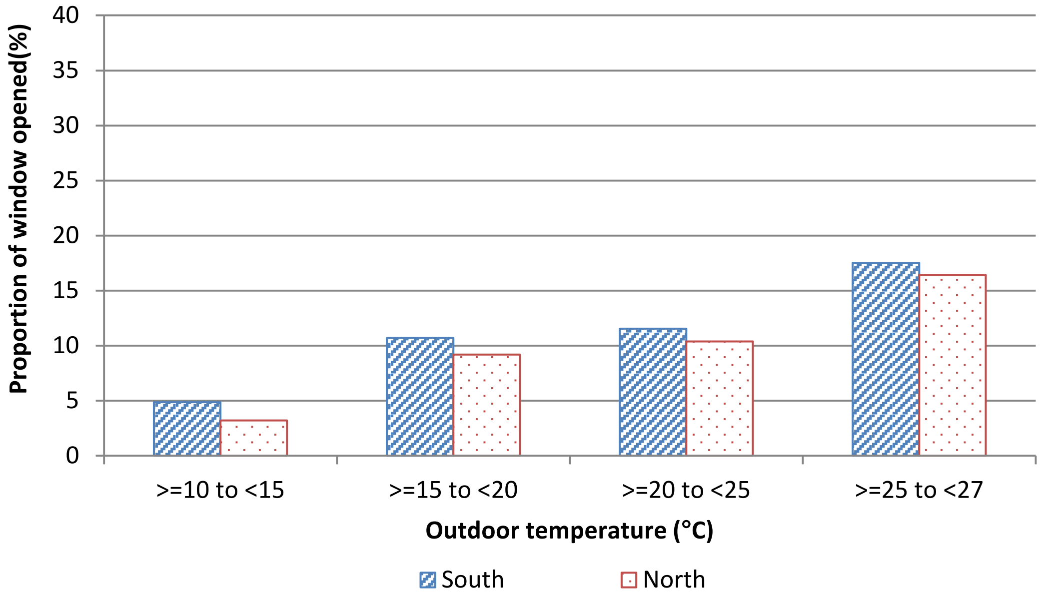
R_{se} is the resistivity of the "air boundary layer" on the outside surface of the wall.

R_1, $R_2, \cdots$, R_n is the resistivity of each component of the walls for the actual thickness of the component used. Therefore, U-value is equal to the inverse of the sum of the thermal resistances of each layer.

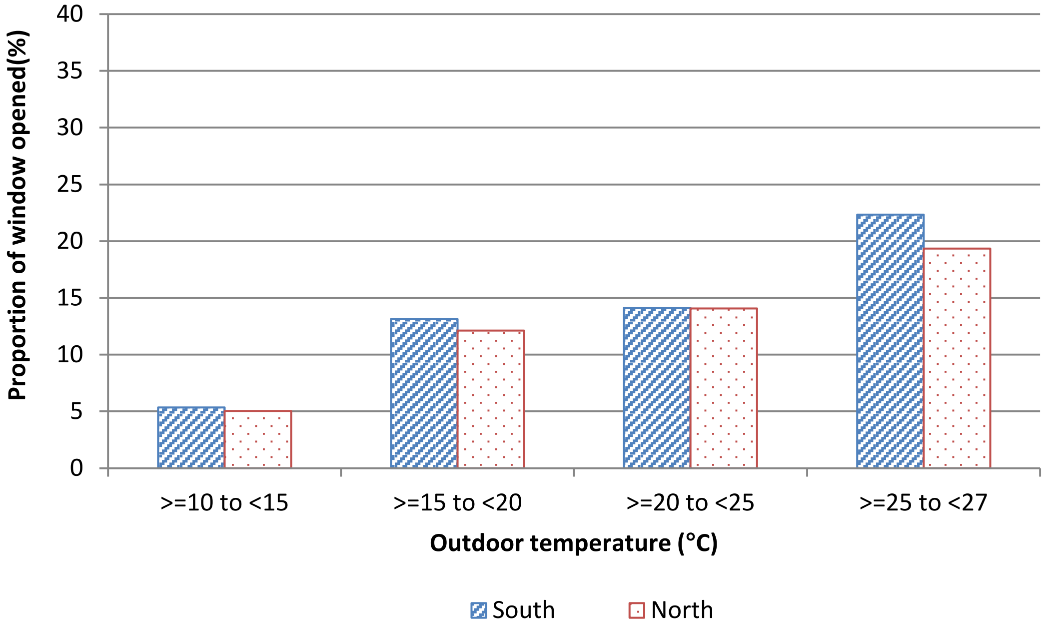
Appendix F

As it mentioned in section 4.3.1.5, this appendix presents the orientation of room have impact on window opened in each new apartment

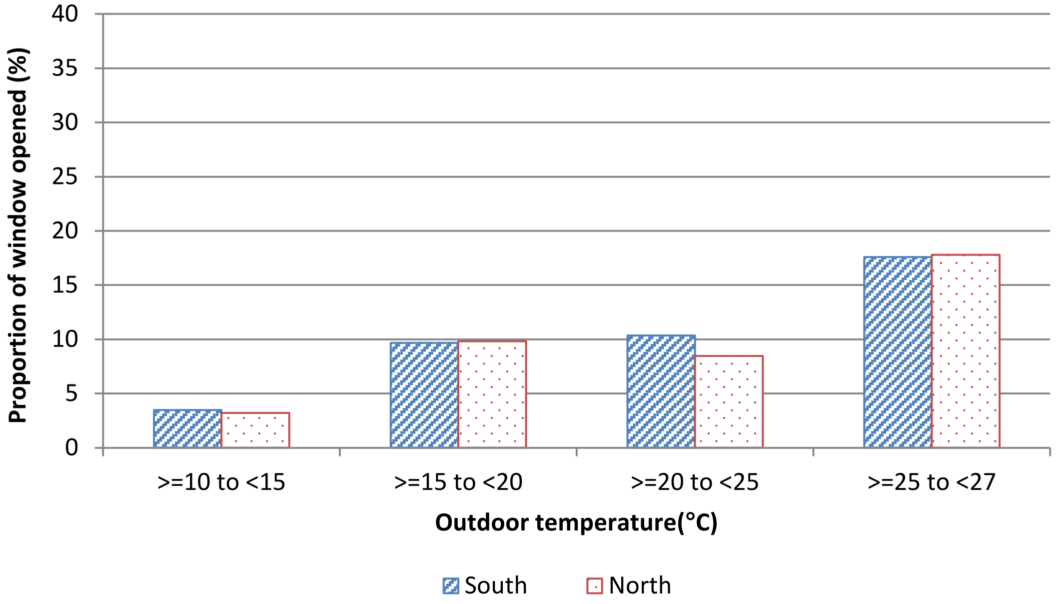
New apartment 1



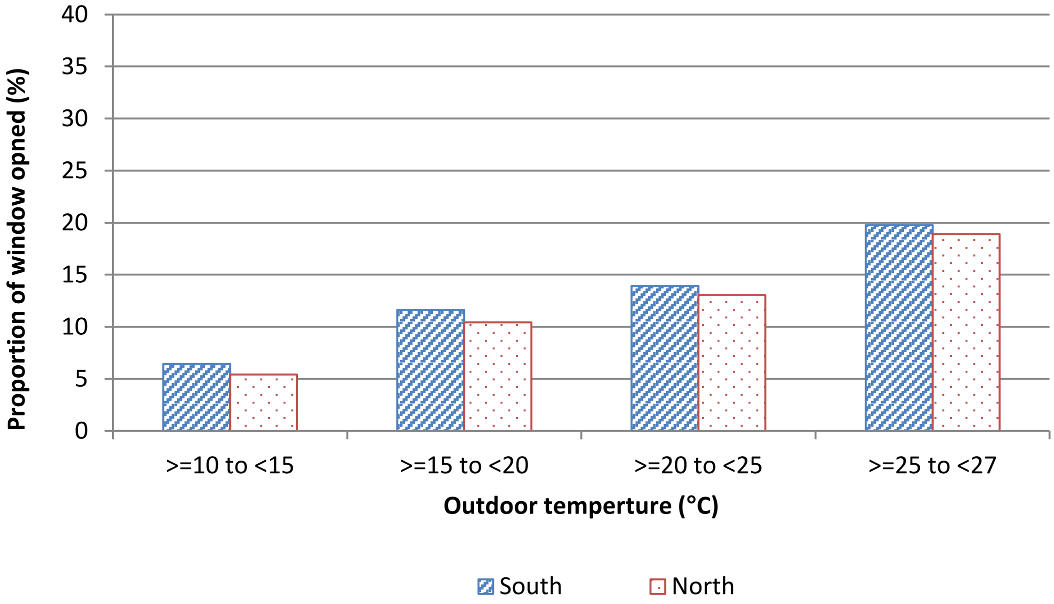
New apartment 2



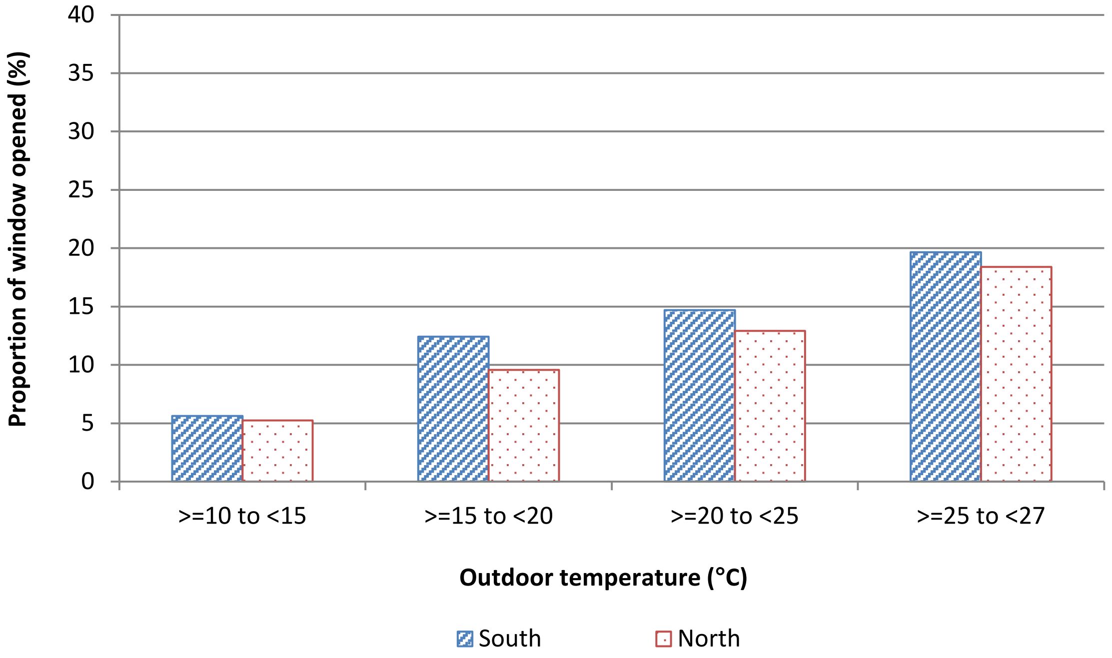
New apartment 3



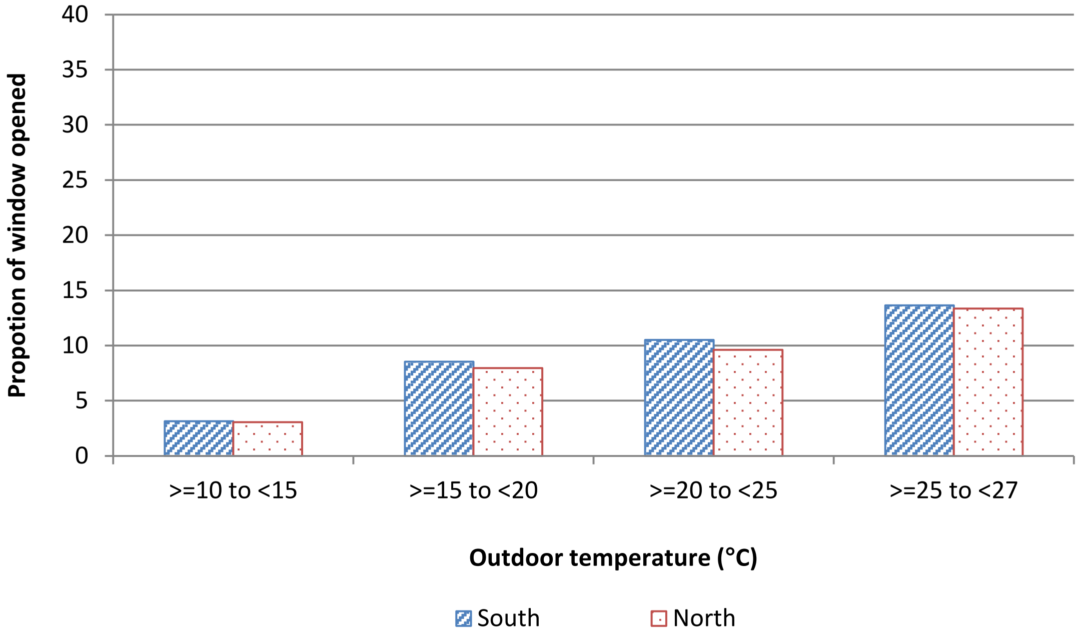
New apartment 4



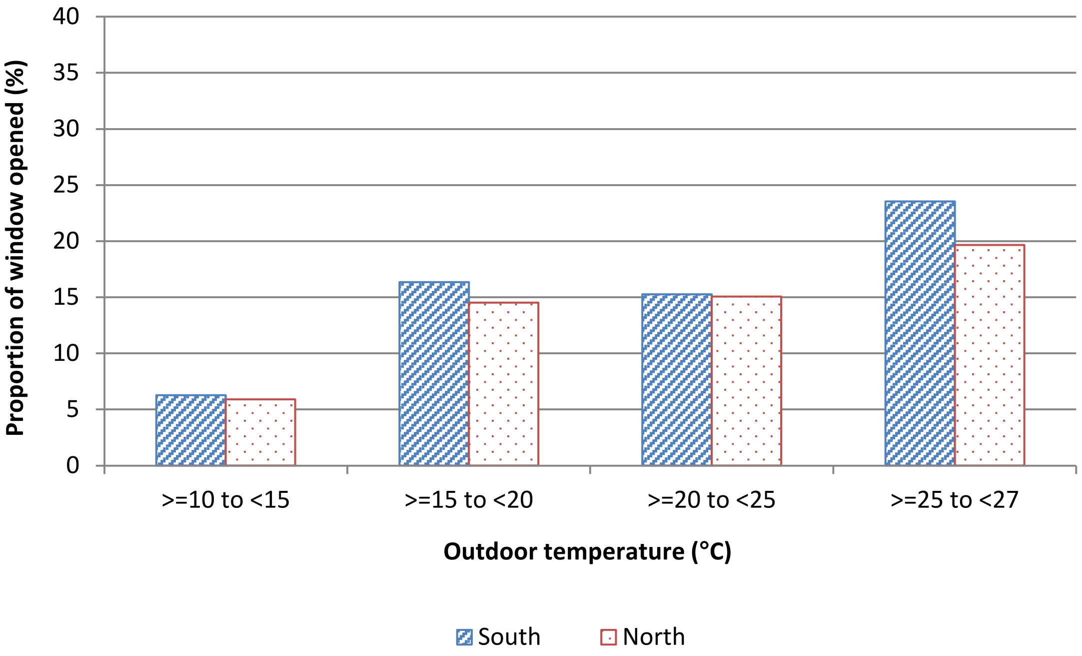
New apartment 5



New apartment 6

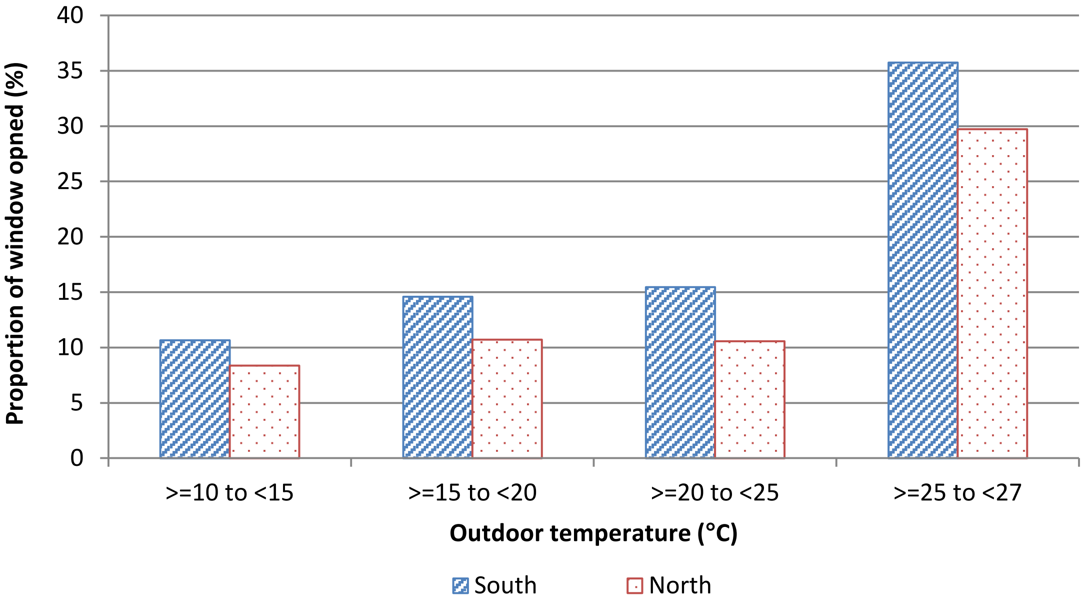


New apartment 7

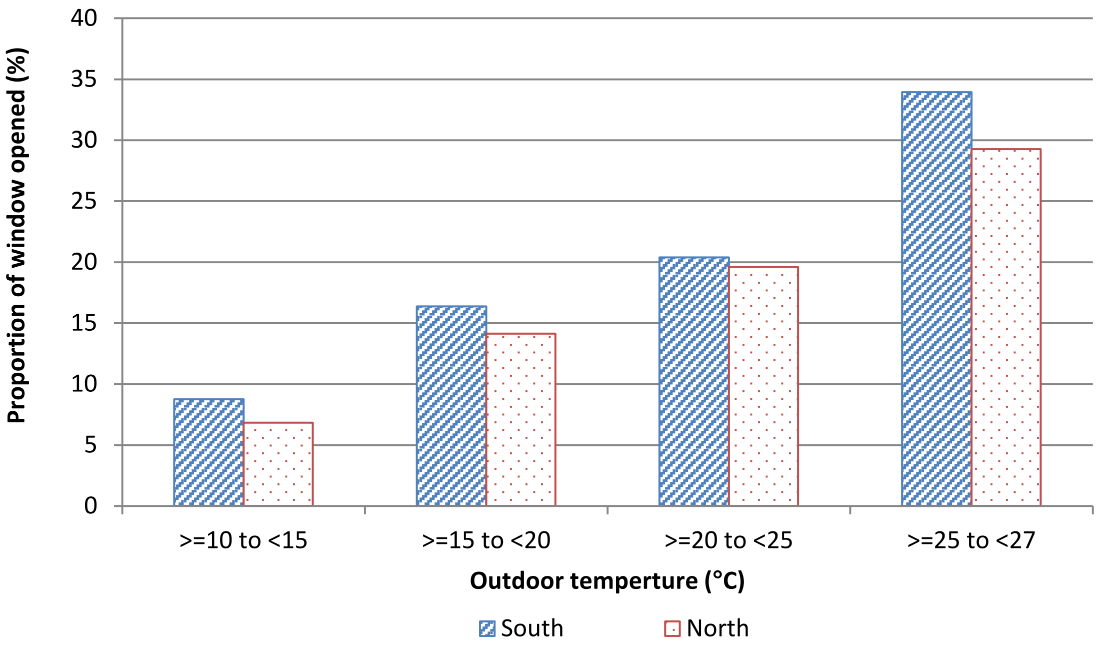


The following figure in this appendix present the orientation of room have impact on window opened in each old apartment

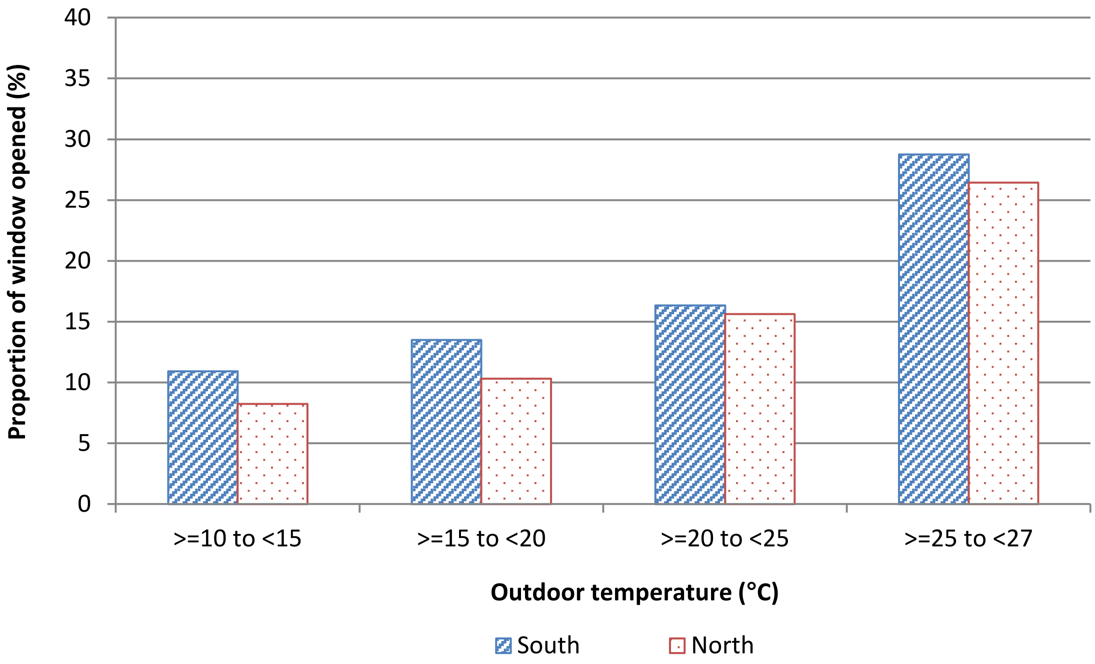
Old apartment 1



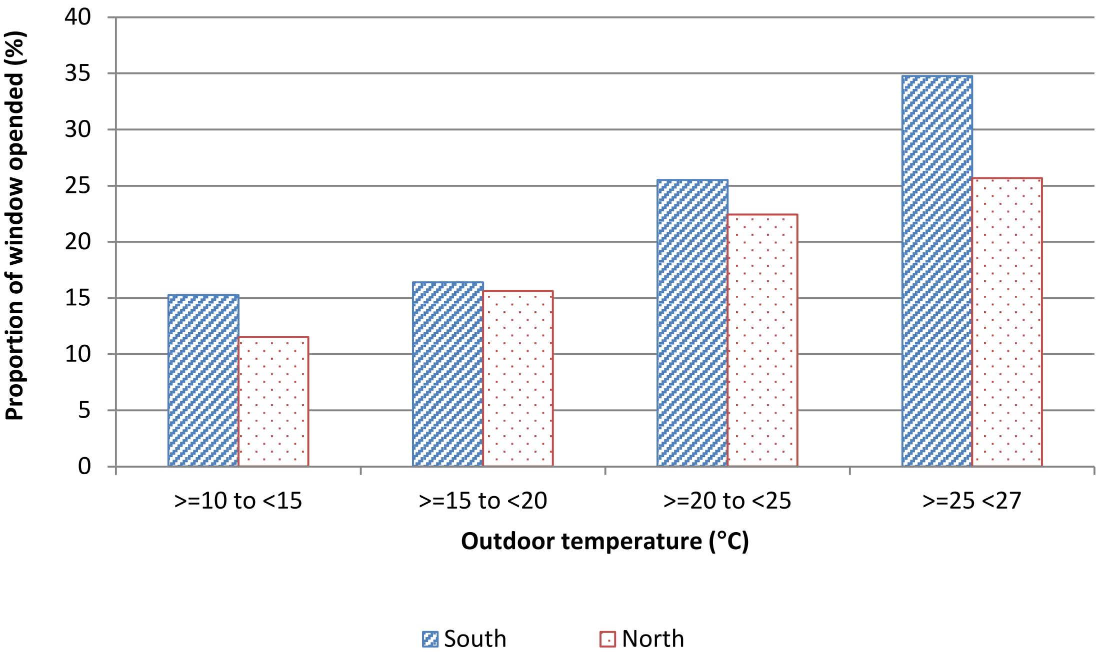
Old apartment 2



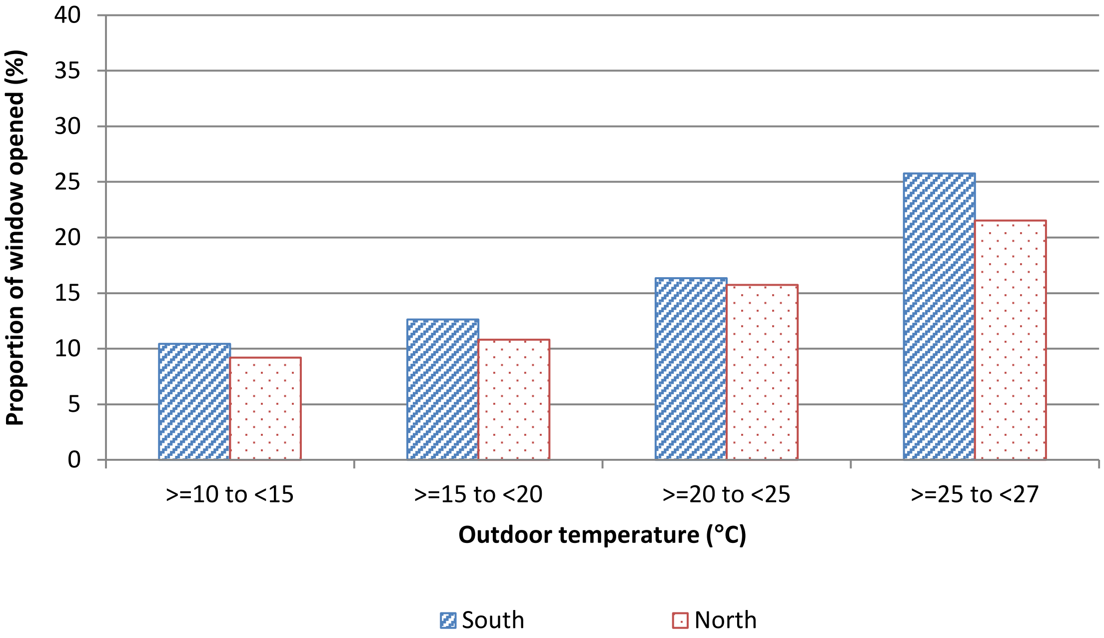
Old apartment 3



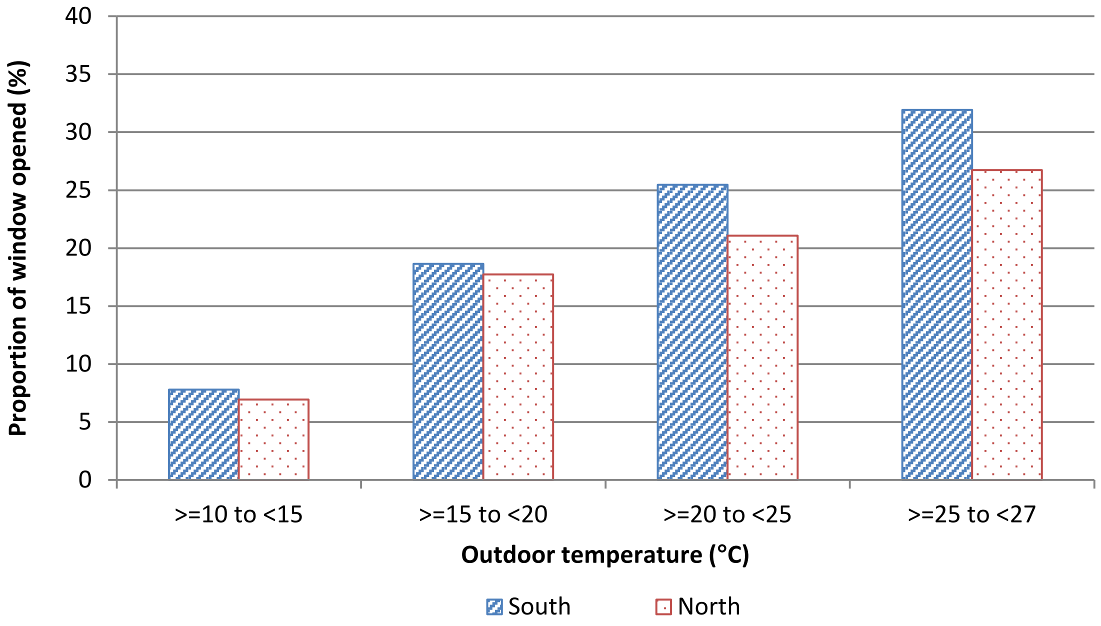
Old apartment 4



Old apartment 5



Old apartment 6



Old apartment 7