

# Study on Adaptive Thermal Comfort and Occupant Behavior in HEMS Managed Residential Buildings

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**Abstract:**

Human behavior is experienced throughout an entire lifetime. Behaviors are impacted by certain traits each individual has. Adaptation is one of the forms of a behavior. Generally, human adapt two conditions. One is to fit with the surrounding environment and the other is creating an environment to fit oneself. Adaptive behaviors equally play an important role for the better thermal environment indoors. The indoor energy use is associated with the trend of energy use.

The total electricity consumption of the Japanese household sector has increased rapidly since in aging and information oriented society utilize more electrical appliances, so energy saving is one of the essential task in Japanese residents. To understand the way of energy consumption and demand response of the residential occupants, it is important to understand the structure of energy use. HEMS (Home Energy Management System) is one of the important tools to understand the pattern and the structure of energy consumption. HEMS is a visualization of the energy usage by connecting the electrical equipment in the home, can automatic control of energy to control each device, and to manage the power saving. The HEMS concept has entered the mainstream of the market. HEMS startups hit the market in 2008 and 2009. The Japanese government has announced the energy use target that should be completed by 2030. To achieve this target of energy reduction, the knowledge about the global market of HEMS, the condition of energy saving and the usefulness of the HEMS to maintain thermal comfort is essential. The changing structure of HEMS globally redirects the HEMS market in Japan.

The usefulness of HEMS systems depends on the thermal comfort and the satisfaction level of the occupants living under the use of this system. There should be a clear knowledge required about the indoor thermal environment under the use of HEMS system. What are the adaptive activities adapted by the occupants for thermal comfort adjustments? Were they fully dependent on mechanical heating and cooling or not?

The objective of this study is to understand the HEMS market in different regions and also to observe HEMS scope for the future. Our objective was also to find out the level of thermal comfort of the occupants living with HEMS systems. What are the adaptive activities taken during the use of HEMS is also one of the concern of our study?

Different journal papers and conference papers were reviewed to understand the increasing pattern of HEMS market in different regions of the world and in Japan.

From the review of the papers related to the HEMS and energy management, we collected the

percentage of energy saving, HEMS global market, HEMS types and HEMS service providers according to different research conducted in different parts, and the mean value of the energy saving was calculated. The condition of global HEMS market and HEMS vendors were identified and.

In order to investigate the occupants' adaptive behaviors for thermal comfort adjustment in a condominium equipped with Home Energy Management System (HEMS), we conducted a measurement survey and thermal comfort survey from November 2015 to October 2016, and 17026 votes from 33 males and 37 females from 47 families were collected. The collected data have been categorized into Free Running (FR), Cooling (CL), Heating (HT) mode and Mixed mode on the basis of heating and cooling use.

The literature review result showed that the Asia pacific region is the second biggest HEMS user region after North America. Approximately, 14% energy saving is possible if HEMS is applied. The global HEMS market was 1500 million USD which increased by 2.1 times and reached 3200 million USD by the beginning of 2016. The results also showed that the users were found to be very active using HEMS services at the beginning but gradually they lost their interest. HEMS needs to be improved to be more applicable to be used in the future

The field survey result showed that the thermal sensation and overall comfort level of the occupants is high. The occupants residing in that HEMS building are satisfied and they have accepted the thermal environment. The indoor air temperature was quite dependable to outdoor air temperature in FR mode. In CL mode, the mean indoor air temperature was 27.9°C which is quite close to mean outdoor air temperature. In HT mode, the mean indoor air temperature was above 20°C. Similar temperature was observed even in FR mode during winter. The thermal sensation vote of the occupants for neutral was high. The overall comfort was also high. The mean clothing insulation was different according to seasons which were 0.43 clo in summer and 0.89 clo in winter. The occupants were adapting window opening behaviors equally other than cooling use to adjust thermal comfort during high indoor or outdoor air temperature in summer. The use of fan increased as the indoor air temperature increased. The occupants were observed adapting passive behaviors rather than active behaviors for thermal comfort adjustment. Heating and cooling was used only with low or high outdoor

air temperature. The occupants were also adjusting clothing insulation for thermal comfort upon their necessity.



# Chapter 1: Introduction

## ***1.1 Behavioral study***

Behavioral sciences contain psychology, psychobiology, anthropology, and cognitive science. Generally, behavior science deals primarily with human action and often seeks to generalize about human behavior as it relates to society. Human behavior is the responses of individuals or any groups of humans to internal and external stimuli. Social behavioral studies are the influence of social interaction and culture. Social behaviors depend heavily upon social norms and are regulated by various means of social control. But humans are free to perform any types of behaviors for individual benefit that does not harm other's individual rights.

Human behavior is experienced throughout an entire lifetime [1]. It includes the way they act based on different factors such as genetics, social norms, core faith and attitude. Behaviors are impacted by certain traits each individual has. The individuality varies from person to person and can produce different actions or behavior from each person. Social norms also determine the behaviors. Due to the naturally traditionalist nature, humans are pressured into following certain rules and displaying certain behaviors in society, which conditions the way people behave. Different behaviors are deemed to be either acceptable or unacceptable in different societies and cultures. One's attitude is essentially a reflection of the behavior he or she will portray in specific situations. Thus, human behavior is greatly influenced by the attitudes we use on a daily basis. So far, the above information shows that the behaviors are unbreakable facts related to human life. So, behavioral study is important to be included in any types of thermal comfort surveys. The behavioral activities and behavioral opportunities should be addressed in any types of theory or model related to human thermal comfort.

Adaptation is one of the forms of a behavior. The term adaptation commonly derived from biology. How the animals and plants adapted to survive in terms of the environmental change. How they fit themselves to the surrounding environment. The history shows that some of the animals like dinosaurs could not adapt with the changing environment and extinct from this world.

Generally, human adapt two conditions. One is to fit with the surrounding environment and the other is creating an environment to fit oneself. Thermal environment is associated with human health because it is very important to keep the body warm or

cool in terms of the outdoor environmental change. There are mainly two ways of keeping warm or cool. One is using some artificial or mechanical devices and the other is using some natural means. The developed countries have full access to the mechanical devices for heating and cooling so are adapted to the use of mechanical means. But, there are still a huge group of communities which do not have access to the mechanical means especially, the developing and undeveloped countries. This group takes various natural behaviors to keep them warm and cool and they are adapted to the use natural means. So, adaptive behaviors are always different according to places, people and environment and equally play an important role for the better thermal environment indoors. The indoor energy use is associated with the human behaviors they adopt.

If we observe the current scenario of energy use worldwide, we can find three major conditions of human adaptation as shown in Figure 1.1. One is the active group adapting with the condition without the use of fossil fuels. This group does not use mechanical heating or cooling devices. The occupants of this group fully adapt natural means for adjusting thermal comfort. They were observed very active and dynamic performing behaviors like window opening, adjusting clothing insulation taking hot or cold drinks and taking some traditional methods like the use of firewood to keep warm. They are fully adapted to such environment. Especially, South-Asian and South-American countries seem adapting this types of behaviors. The reason behind this might be economical or socio-cultural. Another group is passive group with the condition of mechanical heating and cooling use. This group fully depends upon mechanical devices for thermal comfort adjustments. The occupants of this group are adapted to such environment. They think that the thermal environment can be controlled only with the use of mechanical devices. Especially, the European society can be categorized in this group. Now, the third one is the group adapting mixed behaviors. In this group, the occupants are living with all the facilities of mechanical systems but they are not fully dependent on mechanical heating and cooling. They are adapting the thermal environment with mechanical use as well as they are equally adapting active behaviors like window opening, using fan or adjusting clothing insulation. They may be conscious about energy saving and environmental issues but they were adapted with mechanical use or no use according to the necessity. Currently, such types of behaviors are observed in Japan, China and North-American countries.

So far, the researches of all these three sectors shows that human adaptation to the thermal environment is different according to places and economical status. In one hand, the active group without the use of fossil fuels is luring to the charm of life of passive group with the use of mechanical systems but on the other hand, the passive groups were observed gradually turning to active groups adapting mixed behaviors.

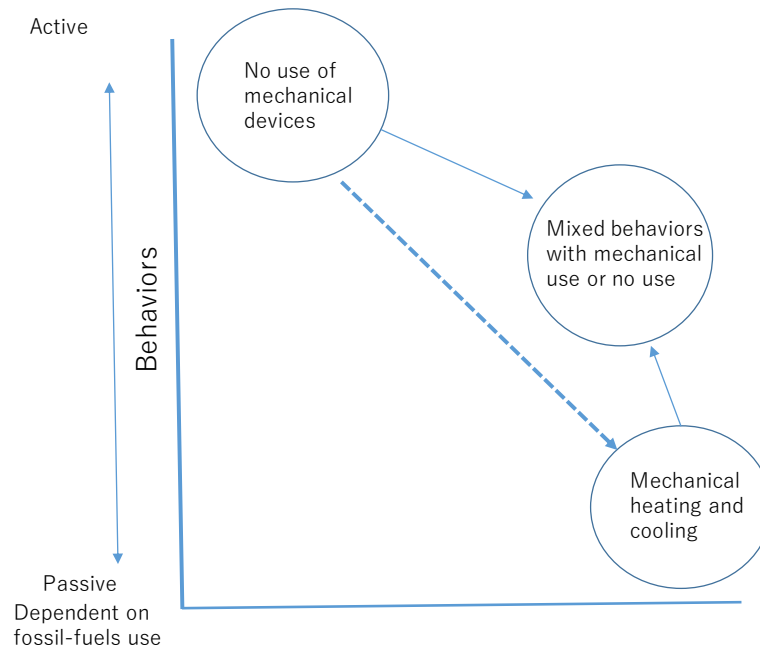


Figure 1.1 Current conditions of human adaptation for thermal comfort.

In this study, we focus the human behaviors adapted for thermal comfort adjustments. Any human generally adapts different activities for to keep himself/herself comfortable. In fact, we all have opportunity to create our mini thermal environment with or without using mechanical systems. When we are living in group there are some limitations and boundaries of social norms and values but when we are living in our personal residents we have more opportunity of adaptive activities. Many researchers have proved that the occupants took many adaptive activities like adjusting clothing insulation, opening windows along with the use of heating and cooling in office buildings, residential buildings and even in factory buildings. But the adaptive behaviors and adaptive opportunities are always ignored by the standards and guidelines. This study focuses additional information in the field of adaptive behavioral study. We have focused our study about the adaptive activities during smart living with unique energy management system. The use of modern electrical appliances has made the life style easier. Different

systems have been used to control indoor thermal environment and the trend of energy use.

## ***1.2 Home Energy Management Systems (HEMS)***

Home energy management system (HEMS) is an effective hardware and software system that facilitate home users to monitor and reduce energy consumption of the various electrical devices installed in their homes. HEMS comprises five different products, which assist in managing and reducing energy consumption. These products include self-monitoring systems, lighting controls, programmable communicating thermostats, advanced central controllers and intelligent HVAC controllers. With HEMS, end-user can access real-time energy consumption data through mobile phones, tablets, and other communication devices to monitor and manage energy consumption in the house [2]. In addition, HEMS provides updates on fluctuating electricity prices to assist users to use less energy during peak hours. Presently, the spiraling energy prices have fostered the demand for energy management. The growth of the world HEMS market is mainly driven by the growing awareness of energy management and rising investment in smart grids. However, high cost of implementation of HEMS technology would impede the growth of the HEMS market.

The total electricity consumption of the Japanese household sector has been increasing rapidly since in aging and information oriented society utilize more electrical appliances to make, so energy saving is one of the essential task in Japanese residents. To understand the way of energy consumption and demand response of the residential occupants, it is important to understand the structure of energy use. HEMS (Home Energy Management System) is one of the important tools to understand the pattern and the structure of energy consumption. HEMS is a visualization of the energy usage by connecting the electrical equipment in the home, can automatic control of energy to control each device, and to manage the power saving. As displayed in Figure 1.2, the HEMS system can be observed and the energy used can be seen by using any handheld devices like mobile phones, tablets or computers. The HEMS concept has entered the mainstream of the market. HEMS startups hit the market in 2008 and 2009 [3]. The Japanese government has announced the energy use target that should be completed by 2030. To achieve this target of energy reduction, the knowledge about the global market of HEMS, the condition of energy saving and the usefulness of the HEMS to maintain thermal comfort is essential. The changing structure of HEMS globally

redirects the HEMS market in Japan [4]. The usefulness of HEMS systems depends on the thermal comfort and the satisfaction level of the occupants living under the use of this system. There should be a clear knowledge required about the indoor thermal environment under the use of HEMS system. What are the adaptive activities adapted by the occupants for thermal comfort adjustments? Were they fully dependent on mechanical heating and cooling or not?

Figure 1.2 HEMS Visualization of energy used in a handheld device

The Home Energy Management Systems (HEMS) are connected from the visualization of electric power use to create smart home environment to power manage of home appliances [2]. As shown in Figure 1.3, the electrical devices that have been used in the home are all connected with the systems. HEMS device users can browse about power consumption for every HEMS-supporting electric home-use appliance based on smart phones, tablets and other types of hand-held devices. HEMS is a system for cleverly managing the various types of energy used in the home. Installing HEMS makes data on electric power generation and utility usage as well as gas and water used amounts visible on monitors and other screens, facilitating control of HEMS-compatible household devices.

By making the electricity used by home appliances visible, each member of our family will become more aware of saving energy, waste use of electricity will be eliminated and energy costs will thus be reduced. And when we go out, we will be able to control energy use by switching off all HEMS-compatible appliances with a single action, thus avoiding energy wastage such as forgetting to turn off devices.

Shared communication protocols are necessary to achieve two-way communication between HEMS controllers and various home appliances, household devices, etc. ECHONET Lite Specification claimed that they are providing this function. With HEMS controllers adopting ECHONET Lite and devices compatible with HEMS, it should become possible for different manufacturers' products to be connected together for use [4].

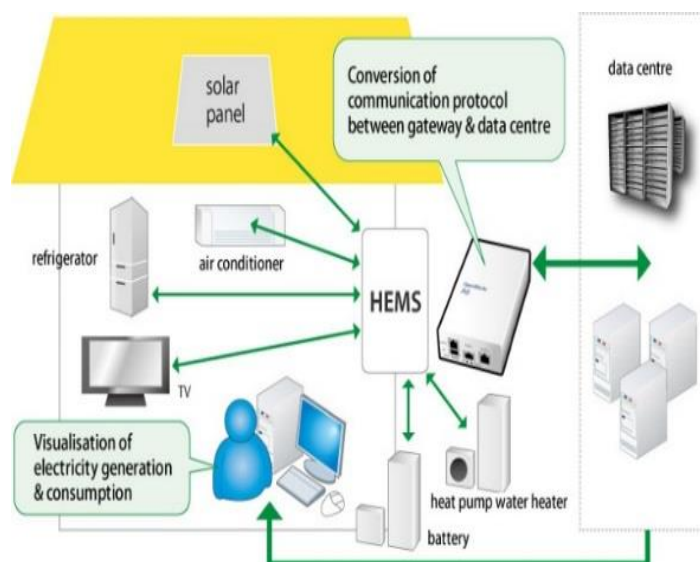


Figure 1.3 HEMS system configuration [4]

On the household, there is a need to guarantee the stable supply of power by maintaining a power supply-and-demand balance between the distribution system and households. Smart house and smart living concept that will further ensure the energy-savings and efficient energy use by equipment installed in the home. At the same time, the number of senior citizens has been increasing in Japan. It is predicted that the percentage of households whose members are aged 65 years or old will reach 38% of all households by 2025. In fact, it is further predicted that the percentage of households whose members are at least 75 years old will reach 20%, meaning that one household in five will be an elderly household of people aged 75 or older [4]. There is

the importance of daily living assistance that allows senior citizens to manage their health and live with peace of mind. HEMS needs improve the way of functioning addressing all these issues. The ECHONET CONSORTIUM is one of the Japanese company claims that they are working for the standardization of home network infrastructure technology. They also claim that they are improving standards and actively participating in national projects, while also promoting activities to support the global development of home networks as shown in Figure 1.4.



Figure 1.4 Smart house network systems [5]

### 1.2.1 HEMS Vendors

The HEMS system includes chip manufacturers and suppliers, device manufacturers, technology providers, software / service providers, system integrators, distributors, and users, as important elements. There are many large and small companies providing HEMS services and HEMS appliances in US, Canada and in Japan [5]. We can see the list of some of the major companies which are providing HEMS services in the world in Table 1.1. In Canada, instead of private companies, the province government itself manages the HEMS services. Toshiba began to sell its HEMS-centric smart household appliances in October 2013. From the research reports and articles, we came to know that in HEMS houses the members is 75% cooperative towards energy saving but in the houses without HEMS members was only 45% cooperative towards energy saving in Japan [2]. So, to increase the cooperation of the members towards energy saving, HEMS area should be increased. After coming up with a successful technology to put in the systems (HEMS) vendors have to think about payment operations sustainable business project. The subscription revenue model should be clear and sustainable for

the users. Still the house owners seem less influenced by the utility of the HEMS. The reasons are high initial cost and the availability of the HEMS related appliances. Another reason is the dwellers are not seen so much aware of energy saving. The HEMS users were also observed gradually losing their interest to the regular use of HEMS. So the HEMS venders need to be much more conscious about the HEMS software. They need to rethink and consider the interest of the users as well as the facilities to be given.

Table 1.1 Major HEMS service provider in the world

S.N.	Country	Name of HEMS Service providing Companies
1	United States	Honeywell International, Inc., Energy Hub, Inc., Nest Labs, Inc., General Electric Company, Vivint, Inc., Alarm.com
2	Canada	Eco bee
3	Japan	Panasonic Corporation, Toshiba, Sharp, Mitsubishi Denki

### 1.2.2 HEMS situation in the world and in Japan

Home energy management system (HEMS) is an effective system that facilitates home users to monitor the energy use. The wastes energy used is easily identified which may help to reduce energy use of the various electrical devices installed in their homes. According to the report of Market Watch, in 2017, the global Home Energy Management System (HEMS) market size was 1220 million US\$ and it is expected to reach 6000 million US\$ by the end of 2025 [5].

The world home energy management system (HEMS) market has been divided on the basis of available types of product, communication technology and geography. Based on components, the HEMS market is segmented into hardware and software. Hardware is sensor, controller & others. Furthermore, the market has been sectioned on the basis of communication technology. The world home energy management system (HEMS) market has been analyzed based on geographical regions, which include North America, Europe, Asia Pacific and Latin America Middle East and Africa (LAMEA). Figure 1.5



shows the HEMS revenue worldwide. It shows that the HEMS revenue market reached from 1500 million US dollar to 4200 million US dollar in 2017 [5].

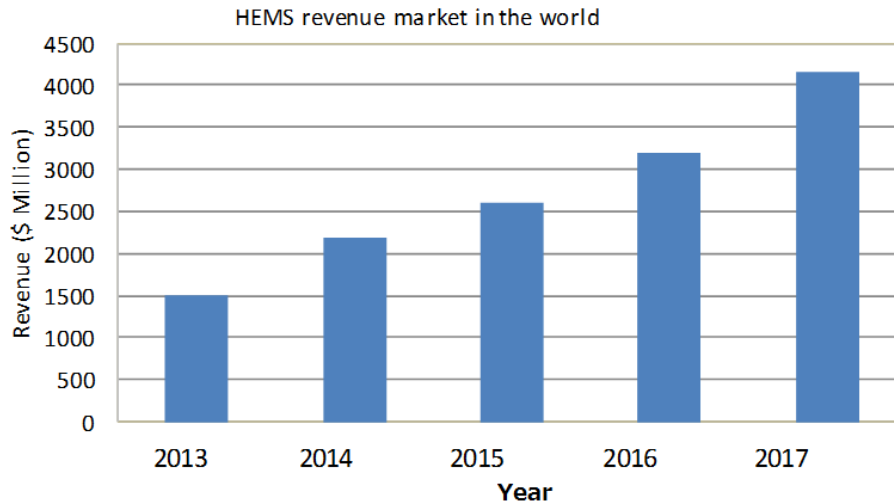


Figure 1.5 HEMS revenue in the world.

The key market players profiled in the report include Schneider Electric, Panasonic Corporation, General Electric Company, Emerson Process Management and others [2]. Smart home is a system that allows home owner to control and monitor different devices in home including the heating, lighting, security, and entertainment, automatically and sometimes remotely via the Internet.

In Japan, there is a demand for a safe and secure living environment, especially concerning safety functionalities and discrete monitoring for elderly people [6]. The use of HEMS is also applicable not to manage energy use only but also to reduce so called CO<sub>2</sub> emission [2]. The need for reducing fossil-fuel use while promoting the renewable energy use is underscored by the events such as the Tohoku Earthquake 2011, which resulted in serious electric power shortages across Japan. Such events highlight the growing need of proper energy management in Japan. According to the report of business wire [7], the number of smart home in Japan is anticipated to reach nearly 7 Million by 2024. Panasonic Corporation and Sony Corporation are the key company working for HEMS services in Japan.

HEMS entered in Japanese market since 2008 [3]. Figure 1.6 shows the HEMS revenue in Japan. This figure shows that the HEMS revenue was 590 million US dollar in 2010 which increased and reached 1800 million US dollar in 2015.

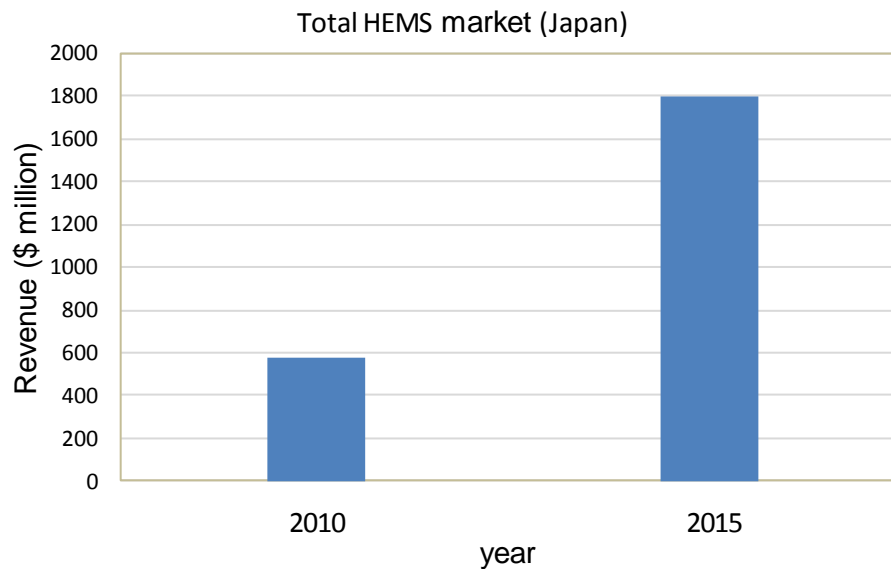


Figure 1.6 HEMS revenue forecast in Japan [6]

Toshiba began to sell its HEMS-centric smart household appliances in October 2013, which can perform a number of advanced concierge services such as remote-control, remote-confirmation, malfunction diagnosis, usage recommendation, energy-saving proposals and notification of operation. According to GMT forecast [8], the cumulative number of HEMS device users will grow from 260,000 in 2014 to 1.6 million in 2020. The launch of the Internet-connected, cloud-service accessible Felinity series of home appliances further enhance Toshiba's smart home appliance services, which can be controlled using PC systems, TVs, and tablets in addition to smart phones. At present, Japan-based household appliance suppliers, including Toshiba, Sharp, Panasonic and Mitsubishi Denki, have already made the controls and operations of their smart household appliance systems through smart phones as standards, sales of smart household appliances compatible with home energy management system (HEMS) are expected to increase significantly amid rising awareness of energy saving and to become an emerging trend of Japan's smart household appliance industry, according to Digi times Research [9].

Sharp has regarded the development of sweeping robots as the first step to realizing next-generation smart home appliance solutions. It is RX-V200 robot, launched in November 2013, can serve as a home appliance hub that can control and operate a number of household appliances through infrared. The RX-V200 can also apply to cloud

services, to enhance the degree of communications with human beings. Sharp has been emphasizing the connection and communications of its smart household appliances and will incorporate such smart functions to all of its home appliances [10]

Panasonic has been focusing connection between smart phones and smart household appliances and has launched more than 10 related products, offering a number of value-added services through FeliCa and NFC technologies. However, along with the rising concern of energy saving, Panasonic has also begun to step into HEMS compatible products. Digi times Research predicted that 7.5 million smart meters to be installed in Japan in 2015 including replacement of conventional electric meters. Japan's Ministry of Economy, Trade and Industry (METI) [11] reported that Japan will liberalize its power market starting April 2016, allowing users to choose their power suppliers and differential rates, and power suppliers have been boosting installation of smart meters.

According to 10 power suppliers' schedules of smart meter installation, Tokyo Electric Power will complete installation of smart meters for all of its users the earliest by 2020 [12]. On the whole, completion of smart meter installation for low-voltage power users (households, small stores, etc.) was scheduled for 2016 and high-voltage ones (factories, large facilities, etc.) by 2024.

The Japanese government promotes energy efficiency of the buildings and housing field. Specifically, for HEMS. METI [11] provides subsidies for introducing energy management systems in homes and buildings which help manage the energy consumption of appliances such as lighting, air-conditioning, and hot-water supply by using information technology systems. These systems enable automatic management of several appliances simultaneously, leading to energy savings and reduced environmental impact. Currently, HEMS subsidy program is implemented by Sustainable Open Innovation Initiative (SII) under the budget of METI [11].

The FY 26 budget of METI's Agency of Natural Resources and Energy, categorized to approximately 4 billion yen for the promotion of large-scale HEMS infrastructure development with the recognition as the continued key energy efficiency measure in the housing sector. HEMS also integrate IT networks with information on energy supply and use from appliances and hot water equipment. HEMS allow for automated measure and display of energy use information, and thus stimulate energy conservation. (Ministry of Economy, Trade and Industry (METI) [11], In Japan 29% of total electricity has been

used in households. The electricity consumption has increased by 56% from 1990 to 2013 [10]. So, energy saving is one of the essential task in Japanese residents for proper energy management. Japan's energy consumption is around 25 % of that of the U.S., which is the second largest electricity consumer in the world after China. As shown in Figure 3, the HEMS revenue market grew by 2.6 times of the year 2010 to the end of 2015. From 2008 to 2020 the growth rate of HEMS has been estimated to increase by 48% [3]. If this ratio continues, the aims of Japan government to set up HEMS to all of the dwelling by 2030 seems to be fulfilled. Our results also display the fact that in HEMS houses the members is 75% cooperative towards energy saving but in the houses without HEMS members was only 45% cooperative towards energy saving in Japan. So, to increase the cooperation of the members towards energy saving, HEMS area should be increased.

Japan and other nations share many common tasks, including the need to reduce CO<sub>2</sub> emissions, reduce healthcare costs, and build safe, barrier-free societies. Today, Japan also faces difficulty in achieving its CO<sub>2</sub> emissions reduction goal established in the Kyoto Protocol of 1997. Various measures have already been implemented, both in industry and at the household level. Ultimately, however, a more effective resolution of these issues will require a systematic approach integrating many devices and systems. A systematic energy management approach with including other human fundamental issues like human behaviors, socio-cultural aspects as well.

### **1.2.3 The importance of behavioral study in HEMS use for thermal comfort**

The difficulty arises with the categorization of behavior. This has been recently brought to light with the rejection of the new DSM by the British Psychological Society [13]. One can see here that it would be easy for a psychologist to include or exclude an extra aspect of behavior when trying to group aspects of cognition as particular phenomena. Those phenomena are themselves cultural interpretations and do not 'exist' beyond their usefulness as models for the study of behavior. However, these illustrations represent a bottom-up view of how distortions of understanding may arise within a top-down tradition. Allow me, once more, to demonstrate the latter example as a scientist with a top-down approach to psychology might see it. This shows even more vulnerability to error. The intangibility of mental processes means that they are always difficult to define, model, and test. It also means that notions are more difficult to refute because they are not directly measurable. It follows that mentalist approaches to

psychology take an ontological leap whereby mental structures are taken to be real things, rather than just being taken as 'useful'. This, of course, is a fallacy and an error in scientific method.

The alternative is the bottom-up approach. I would argue that in psychology, behaviorism would appear to represent this well. A disregard for the value of the bottom-up building block approach emerged as a radical reaction to disagreements regarding early theories from behavior analysis. Powerful studies by Watson and Thorndike [14] in the early 20th century made people take notice of the behavioral approach.

HEMS visualizes the power use inside the home. As the wastes of the energy are easily identified so the users can control that device. But the major concern is how the occupants behave after the identification of the wastes of the energy. Some researchers showed that if the occupants are getting any subsidies or if they do not have to pay the electric bills, they may not be more conscious about energy saving. But in this study, the occupants are the owner of the flats and they need to pay for their electric bills by themselves. So it would be more useful to have a study in this condominium equipped with HEMS system.

#### **1.2.4 Weakness of HEMS system**

HEMS system just shows the energy using trend of the users by the means of smart meter or other devices. But this system does not have any functions to attract the attention of the users. Some of the results under the use of HEMS system showed that the occupants were more conscious to observe the trend of energy use at the initial stages but gradually they lose their interest [2, 7]. The weakness of the HEMS system is it is not an automatic system as well as it is costly. It needs to be checked regularly for to understand the amount of energy used in the particular device inside the home with this system. There is nothing included to attract the HEMS users for regular check of the HEMS system.

HEMS system needs some software along with the visualization of energy use to get the regular attention of the users. Some useful information of day to day activities of health related tips might attract the attention of the users [14]. So, HEMS system needs

to be reformed with some additional facilities so that the users pay more interest using it.

### ***1.3 Adaptive model and its importance***

Adaptive model describes that the indoor thermal comfort is associated with outdoor thermal environment [16]. The indoor comfort temperature is associated with outdoor temperature in naturally ventilated buildings. But even adaptive model needs to widen its scope. The indoor comfort might be associated with outdoor thermal environment even in the buildings with the use of mechanical systems. There are adaptive opportunities even when the occupants are living with the mechanical systems. It is not sure that the occupants fully depend on mechanical heating and cooling use. In fact, there are more opportunities in residential dwellings. The occupants have private life so they are more open to adapt various activities. So, adaptive model needs to include the activities of the occupants living with mechanical systems as well.

### ***1.4 Comparison of adaptive model with conventional model***

Predicted Mean Vote (PMV) model developed by Fanger [17] describes the chamber based result obtained from a controlled environment. The people were kept in a research chamber for certain period and their votes were taken after certain time. The equation has been calculated and is being used for predicting mean vote. During this experiment the environment of the research chamber was fully controlled. There were no doors and windows in the research chamber. Similar types of the cloths were provided to the people. But in reality, the condition might be different. The clothing insulation might be different, the door and window opening behaviors of the people might be different. The way of heating and cooling use may be more or less. This model ignores the adaptive opportunities of the occupants living in any types of dwellings. People have developed some adaptive activities like window opening, changing clothing insulation and many more to restore their comfort. The conventional adaptive model focuses the impact of outdoor environment to indoor environment. According to adaptive model, the indoor comfort temperature is associated with outdoor air temperature. It also focuses the adaptive opportunities of the occupants but only in naturally ventilated buildings only.

### ***1.5 Objective of this study***

The objective of this study is to observe the indoor thermal environment of the occupants living with the HEMS systems. Indoor air temperature and relative humidity will be observed to know the indoor thermal environment. We will also analyze the occupants adapted active and passive behaviors in terms of that observed environment.

### ***1.6 Outline of this study***

This study is organized to understand the adaptive behaviors of the occupants while living with the use of HEMS system. The living with this system is smart living. The occupants have opportunities to observe the trend of energy used at their homes. They have an opportunity to control their indoor thermal environment. They can easily control indoor electrical devices with their handheld devices. So the general expectation of the people is there might be well controlled indoor thermal environment during the use of HEMS system. The occupants might be fully depending upon the use of mechanical system for thermal comfort adjustments. There needs to take a detailed survey of the indoor thermal environment with the use of HEMS system.

We conducted a measurement survey and online survey for one year to complete this study. Despite of the busy and privacy of the occupants, we were able to collect data for whole year. We have observed the indoor air temperature and relative humidity to understand the indoor thermal environment and adaptive behaviors like window opening, clothing adjustments, fan use, cooling and heating use of the occupants to understand the adaptive behaviors of the occupants. The continue one-year measurement data has been analyzed. This research is unique in a sense that a big data set was analyzed to understand the indoor environment of the occupants living with the HEMS systems.

### ***1.7 Expected results***

Japan is well developed country with maximum use of modern tools and technology because Japan is popular worldwide for its unique technology. Japanese people have full access to the modern tools and technology to make their life easier and comfortable. They are using modern tools and technology maximally. Different types of electrical appliances have been used in Japanese houses to maintain the indoor thermal environment suitable for living. But the problem is more energy has been needed to use

those electrical appliances. What can be done to reduce energy use and to maximize the thermal comfort of the dwellers is always the challenge for new housing developers. Many researchers have shown in their report that there are many activities carried out for energy saving. Those research reports also show that the occupants have adapted with that environment. This study will be an attempt to give detailed adaptive thermal comfort and the occupant behavior of the people of the HEMS managed buildings. We are curious enough that what kinds of behaviors are generally taken for thermal comfort adjustments while using HEMS systems. Though our research is not focused on the use of HEMS systems. Our major concern is to know how the occupants behave in terms of the indoor thermal environment while living and using HEMS systems. To what extent, the occupants are depending upon mechanical heating and cooling and to what types of indoor thermal environment they are adapted.

We expect that the occupants are fully utilizing HEMS system to control the indoor thermal environment. We expect that there are more mechanical devices used to adjust indoor thermal comfort. At the same time, we also expect that the energy use is systematic and limited. Whatever the result will be but the knowledge of adaptive thermal comfort and the occupant behavior of this selected building will be fruitful to the new building designers with same or similar types of energy management systems to design better houses with maximum comfort in coming days here in Japan and outside Japan.

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## Chapter 2: Methodology

### *2.1 Surveyed area and surveyed building*

The study site Shinagawa is in southern Tokyo metropolitan area. Tokyo is the capital of Japan. It is most populous metropolitan area in the world. It lies in the southeastern side of the main island Honshu and include the Izu islands and Ogasawara islands [1]. Tokyo lies in the humid sub-tropical climate zone with hot and humid summer and generally mild winter. The annual average rainfall is nearly 1530 mm with wetter summer and drier winter. Snowfall is sporadic but occurs almost every year. Monthly average sunshine is high almost 175 hours in May and August and low almost 128 hours in September and October. The climate is warm and temperate. There is significant rainfall throughout the year. About 1469mm of precipitation falls annually. The warmest month of the year is August with 31.6°C mean maximum temperature and January has 1.8°C mean minimum temperature. The mean maximum relative humidity is 78.4% in August and the mean minimum relative humidity is 54.7% in January. The mean maximum, average and minimum outdoor air temperature and indoor air temperature variation along with relative humidity in different months will be explained in another section.

An eighteen storied condominium with 356 families shown in the Figure 2.1 was selected for the present study.



Figure 2.1 Studied HEMS managed condominium

The floor plan of one of the studied flat is shown in Figure 2.2. The studied building has 18 story. There are 21 flats in each floors. Most of the studied flats in the condominium are 3 LDK (3 bed rooms, a living and dining room and a kitchen) and very few are 4 LDK (4 bed rooms, a living and dining room and a kitchen). The area of the flats varies from 71 to 90 m<sup>2</sup>.

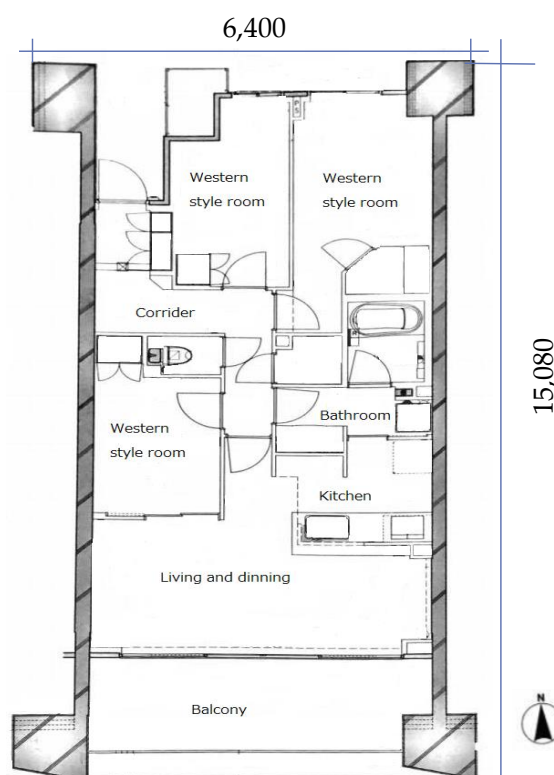


Figure 2.2 Floor plan of one of the studied flat

Table 2.1 shows the basic thermal characteristics of this condominium. The U value mentioned in Table 2.1 shows how much heat goes out from the building envelop. The U value mentioned in each building envelop indicates the amount of heat that goes out from that particular materials. For example, the U value of window is 4.64 [W/(m<sup>2</sup>K)]. It means that 4.64 W/K heat goes out from 1m<sup>2</sup> area of the window. This condominium is made up of Reinforced Cement Concrete (RCC) structure and its construction was completed in 2015.

This condominium is certified as “low carbon architecture (little CO<sub>2</sub> emission and energy saving) according to Japanese building supplementary codes. The studied

building is HEMS managed and equipped with a compact co-generation system so called ENE-FARM as shown in Figure 2.3.

Table 2.1 Basic thermal characteristics of the studied condominium.

Building envelopes	Materials used	U value [W/(m <sup>2</sup> K)]
Wall (external)	RC 180 mm + Urethane spraying 40 mm	0.72
Wall (balcony & corridor side)	ALC 100 mm + Urethane spraying 40 mm	0.75
Roof	Concrete void slab 250 mm + hard urethane foam 50mm	0.59
Window	Double glazing with aluminum frame	4.65

Note: U value of double glazing window includes the effect of aluminum frame.

It is a fuel- cell co-generation system that produces electricity through a chemical reaction between oxygen from the air and hydrogen extracted from natural gas [2] and the heat generated during this process is used for heating water that is used for kitchen, floor heating or other purpose.



Figure 2.3 ENE-FARM

This is a co-generation system developed for this condominium and was installed in each dwelling units. Such installation in condominium has been claimed for the first time in Japan. There are no high-rise buildings around this condominium so natural ventilation performs well. The surrounding environment is very good. There is greenery around and the river flows east to the building.

## **2.2 Online survey**

Online questionnaire survey was conducted to observe thermal comfort level and the occupants' behaviors of the occupants residing in the studied condominium. The occupants were asked a series of questions on thermal sensation, overall comfort and various behaviors taken to adjust thermal environment. The occupants responded to our questions when they had free time using their laptop or mobile phones in the way as shown in Figure 2.4.



Figure 2.4 The online survey method

The responses were automatically restored in the cloud computing systems. To aware the occupants and remind them for to participate in online survey, we frequently visited the studied building and posted the reminding letter to the letter box of all the respondents living in the studied building.

The thermal comfort scale as shown in Table 2.2 has been used. To analyze behaviors like window opening, fan use and the use of heating or cooling, binary data (0 = OFF, 1

= ON) were also collected. The occupants responded whether the door, window or electrical devices were on or off at the time of voting.

Table 2.2 Thermal comfort scale

Scale	Thermal sensation	Thermal satisfaction	Overall comfort
1	Very cold	Very unsatisfied	Very uncomfortable
2	Cold	Unsatisfied	Uncomfortable
3	Slightly cold	Slightly unsatisfied	Slightly uncomfortable
4	Neutral	Slightly satisfied	Slightly comfortable
5	Slightly hot	Satisfied	Comfortable
6	Hot	Very satisfied	Very comfortable
7	Very hot		

The occupants were also asked to vote the level of clothing by taking a look at the chart shown in Figure 2.5. The clothing insulation value was listed as shown in Figure 2. The clothing insulation values have been estimated on the basis of OM Solar Japan similar to the previous study [3]. The occupants were requested to choose the clothing insulation value that fit what they wore at the time of voting. The purpose of the questionnaire was explained to the occupants in advance and also the data obtained were to be used only for statistical analysis. The meaning of the questionnaire was clearly detailed to the occupants of the buildings in advance. The flat code and nickname of the occupants have been used for not to expose the actual identity of the occupants. Altogether, 17,026 votes from 33 males and 37 females from 47 families were received during the survey period from November 2015 to October 2016. The age of these 70 occupants ranges from 15 to 75 years. If the age groups were sorted with an interval of 5 years, the largest number of votes was received from the age groups of 35-39 years, 50-54 years and 70-74 years.

The voting time has been matched with measured data. We classified data into those in free running (FR), cooling (CL) and heating (HT) modes. FR mode means when mechanical heating and cooling devices have not been used. CL mode is when mechanical cooling devices have been used. HT mode means when mechanical heating devices have been used. Recently, the most common approach to show the relationship between external conditions and behaviors is to make a logistic model, namely the stochastic approach which has been introduced by Nicol. We have used the same method to understand the relation of the thermal environment of the building and the occupants' behaviors.

*Please, select the clothing insulation (clo) value that you are wearing now.*

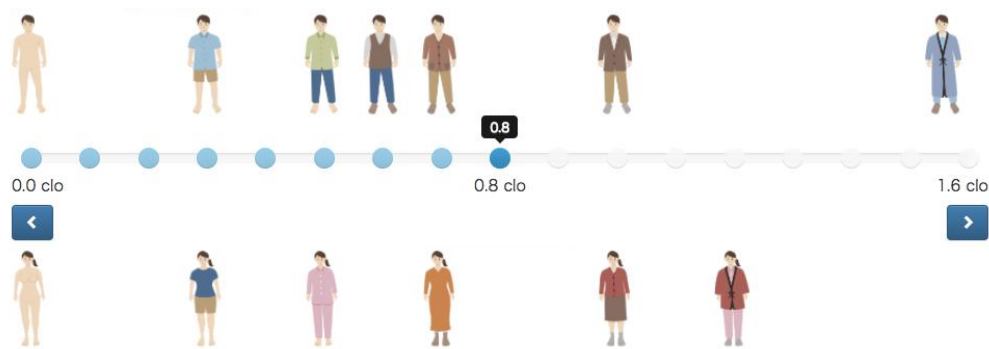


Figure 2.5 Clothing insulation values [10]

### 2.3 Measurement survey

The device as shown in the Figure 2.6 has been placed in every units of the condominium for measurement which records indoor air temperature and relative humidity simultaneously. The measurement was done in a large scale. There was the financial limitation. So we decided to measure indoor air temperature and relative humidity only to understand the indoor thermal environment. There are no high-rise buildings around this condominium so natural ventilation performs well. The air velocity might have definitely played an important role for thermal comfort adjustment inside the studied building. We had no measurement for air velocity so we observed the behaviors like window opening, door open that are related to air movement.

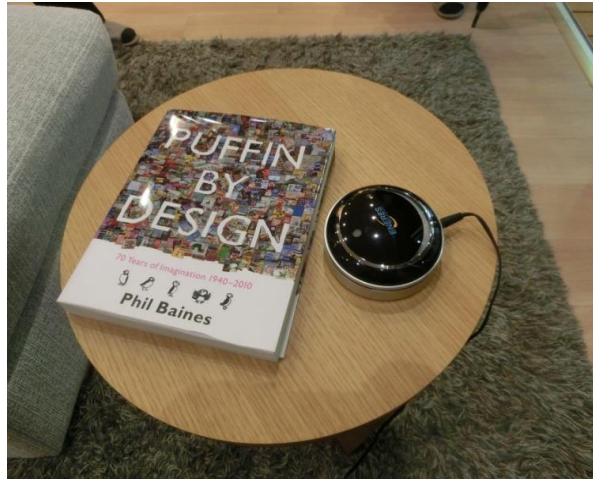


Figure 2.6 Measurement device and its placement

The data was recorded in an interval of 2-10 minutes. The device has the weight of 240g and placed as shown in Figure 2.6 during the measurement.

### 2.3.1 Accuracy of the device

The reliability of any measurement depends upon the accuracy of the sensors used for the measurements. Table 2.3 shows the accuracy of the sensors mounted in the device as shown in Figure 2.6.

Table 2.3 Accuracy of the sensors used for the measurement in the studied condominium

Measurement unit	Accuracy	Limitation
Air temperature	$\pm 2$ °C	0-40°C
Relative humidity	$\pm 5\%$	1-100%
Lighting (1000lx)	$\pm 20\%$	0-5000lx*

\*The device has the capacity to measure up to 6000lx but during the measurement it was limited to 5000lx

The accuracy of the measurement sensors is slightly low for allowing the cheap installation in large scales. The devices were provided to each flat in the condominium so that it was obligation to consider the cost of the devices. For the confirmation of the accuracy of the measurement, we calibrated the actual used sensors with high accuracy



sensors. The measured data has been matched with the voting times of the occupants and analyzed. The outdoor air temperature has been taken from the Tokyo Meteorological Station which is located in Chiyoda district almost 13 km away from the studied building. The study area is closer to Haneda airport but relative humidity data has not been provided by Haneda Airport so we took air temperature and relative humidity of Tokyo Meteorological Station for our analysis. We have compared the monthly mean outdoor air temperature of Tokyo meteorological station and Haneda Airport. As shown in Figure 2.7, there is no such big difference in monthly outdoor air temperature between Tokyo Meteorological Station and Haneda airport. The outdoor air temperature has been provided at an interval of 10 minutes so for uniformity, the indoor measured data has been converted at an interval of 10 minutes.

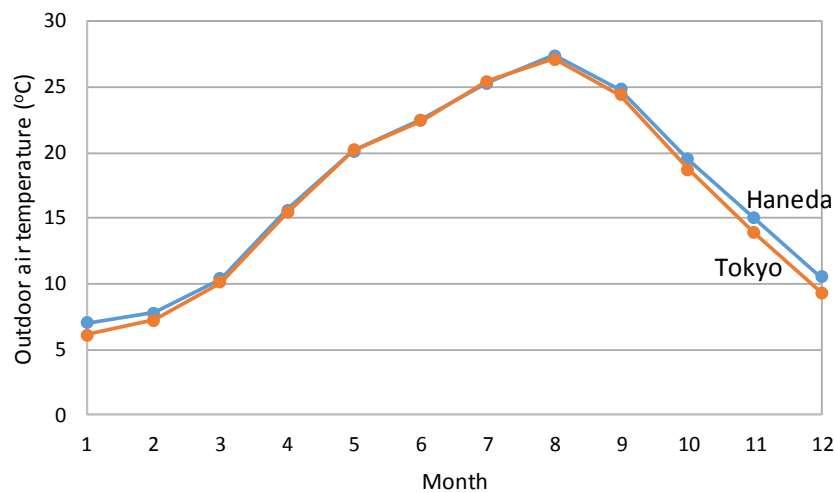


Figure 2.7 Comparison of monthly mean outdoor air temperature of two closest stations

### 2.3.2 Calibration of the sensors

The high accuracy devices were used for the calibration of the device used for measurement in this condominium. TR-74Ui as shown in Figure 2.8 has the accuracy of  $\pm 0.5^{\circ}\text{C}$  for air temperature and  $\pm 5\%$  for relative humidity.



Figure 2.8 High accuracy device (TR-74Ui) used for calibration

The another device TR-52i as shown in Figure 2.9 has the accuracy of  $\pm 0.3^{\circ}\text{C}$  for air temperature. We also used this device for calibration. We took two high accuracy device for calibration for the reliability of the calibration method.

We kept these two high accuracy devices together with the actual devices that is used to measure indoor air temperature in the studied building. The measurement was re-carried out for 15 days simultaneously in three houses equipped with same HEMS systems.



Figure 2.9 High accuracy sensors (TR-52i) used for calibration

Figure 2.10 shows the indoor air temperature variation of three houses (House 1, House 2 and House 3) taken for the calibration of the sensors. The result showed that the actually used device for the measurement in the studied condominium measured slightly higher temperature. Similar result has been obtained for relative humidity as well. The calibration of the sensors of the devices showed that the indoor air temperature and relative humidity would be slightly lower if measured by high accuracy devices.

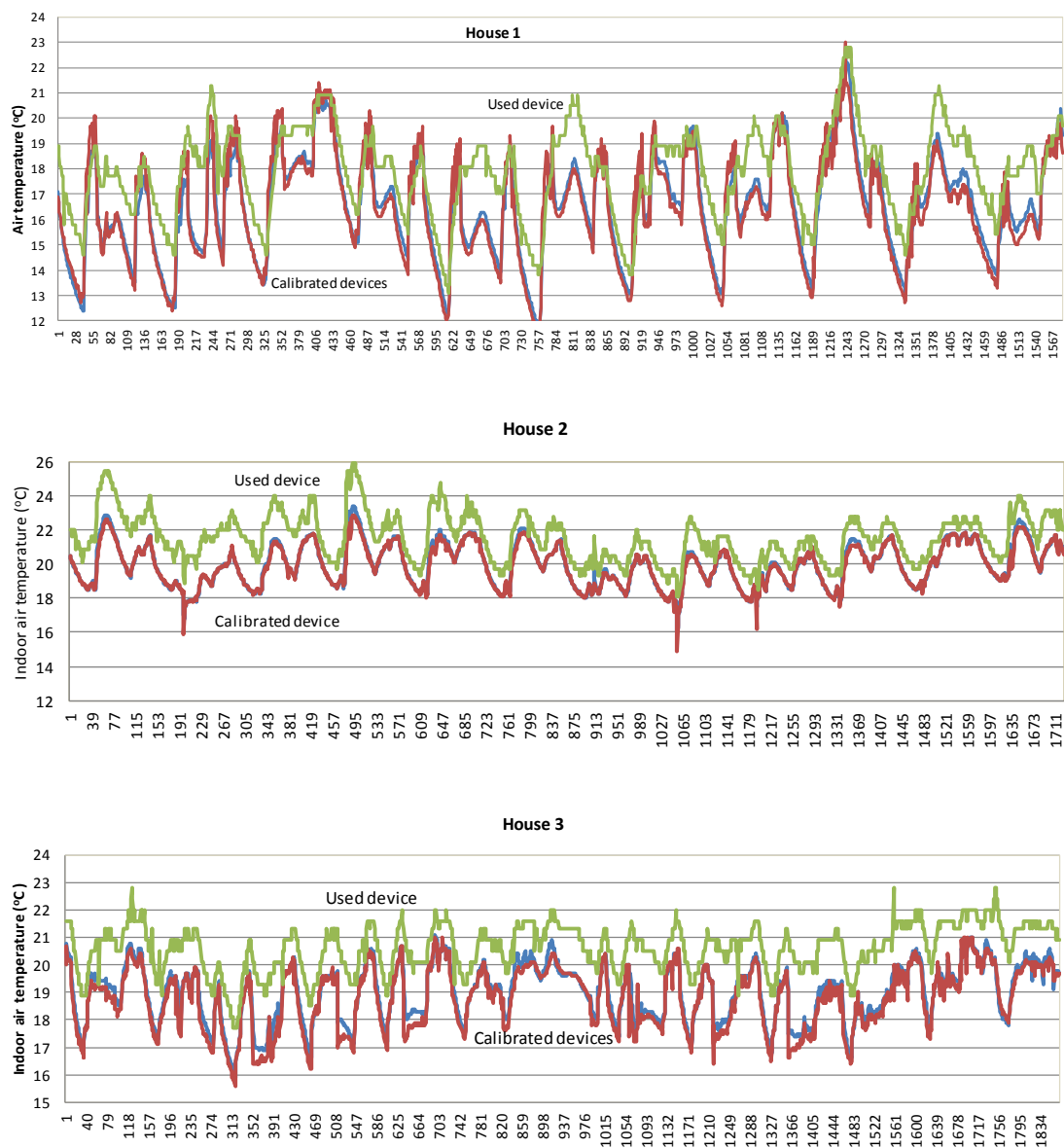


Figure 2.10 Indoor temperature variations of calibrated sensors and actual used sensor

Table 2.4 shows the air temperature difference between the air temperature measured by the HEMS device and the actual temperature to be if measured by high accuracy devices. We have found almost 0.5 to 1.5°C differences between the temperature range of 15-22°C.

So, we did regression analysis of air temperature measured by high accuracy device and low accuracy device as shown in Figure 2.11.

Table 2.4 The temperature differences

HEMS	Actual	Difference
15	14.6	0.4
16	15.4	0.6
17	16.2	0.8
18	17.1	0.9
19	17.9	1.1
20	18.7	1.3
21	19.5	1.5
22	20.4	1.6

The regression equation obtained from the analysis for indoor air temperature were used and we corrected all the data.

The relative humidity measured by the actual device used in the studied condominium was slightly higher than the relative humidity measured by the calibrated devices. Using the equation obtained from the regression analysis between the relative humidity measured by HEMS device and calibrated device, we also corrected all the relative humidity data.

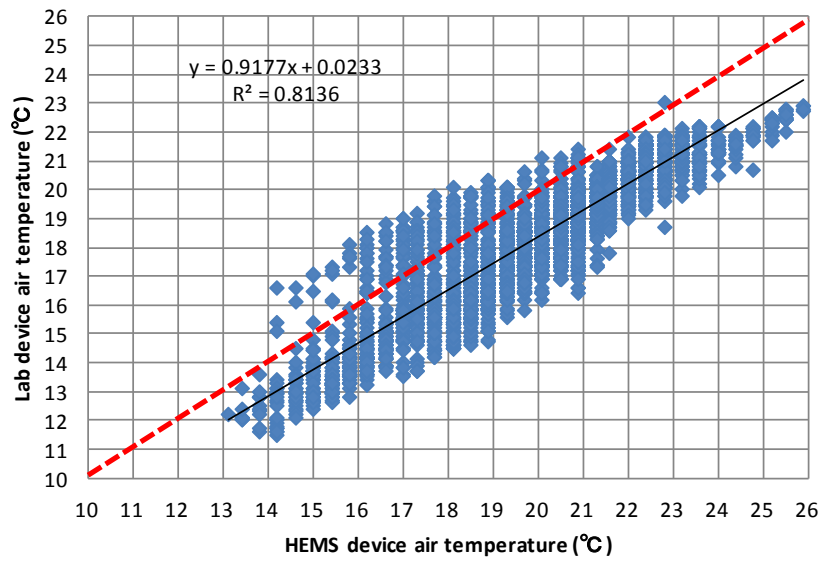


Figure 2.11 Relation between the air temperature measured by HEMS device and calibrated device

We also did similar regression analysis for relative humidity as well as shown in Figure 2.12.

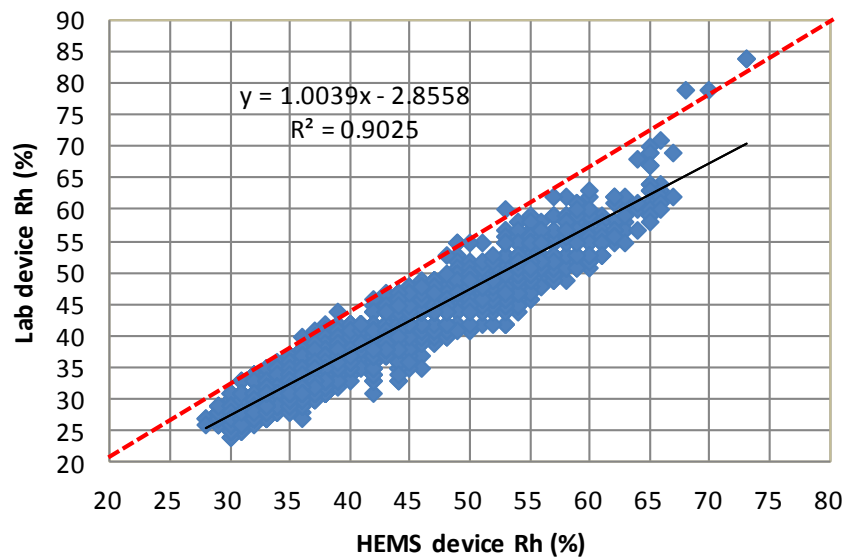


Figure 2.12 Relation between the relative humidity measured by HEMS device and calibrated device

## **2.4 Literature review**

A special literature review has been done to understand the condition of HEMS globally and in Japan [5-18]. More than 21 reports including journals and report have been deeply studied related to home energy management systems only. Among them 7 papers related to energy saving and cost saving were mainly taken to calculate the percentage of energy saving and cost savings. The literature review was also done for to understand various thermal comfort studies conducted in different parts of the world and in Japan. We have found many thermal comfort studies taken in various parts of the world in office buildings and residential buildings. There are some thermal comfort studies in Japanese residential buildings, office buildings and detached houses. We could not find any thermal comfort studies done in any smart living dwellings. As we have already discussed that living with HEMS system is smart living in a sense that the energy used in the home is visualized by the HEMS device so wastes can be easily understood. Besides this, the electrical devices are easily controlled with the hand held devices. It was possible to control the electrical devices used in the homes even when you were not at home. You could switch on or switch off the air conditioning units or lights of the homes from outside of the homes. So, generally a distinct thermal environment can be expected with the use of such systems.

It is very important to conduct research studies and find out the differences in thermal environment between general living and smart living. This study can be also useful to understand the behaviors of the occupants with HEMS systems so that HEMS can be used in an effective way.

## **2.5 Logistic regression analysis**

The logistic regression method as shown in equation 2.1 is used to predict the occupants' adaptive behaviors for thermal comfort adjustments. Nicol and Humphreys [18] made use of logistic analysis to predict occupant control behaviors. We have also applied the same method in this study to observe the proportion of adaptive activities of the occupants for thermal comfort under the use of HEMS. The logistic regression equations for window opening, fan use, cooling use and heating use as their probability as a function of outdoor air temperature were obtained as follows. The relationship between the probabilities of window opening, clothing insulation, heating and cooling use ( $p$ ) and indoor or outdoor air temperature ( $T$ ) is taken:

$$\text{Logit}(p) = \log \{p / (1-p)\} = bT + c \quad (2.1)$$

Here, exp (exponential function) is the base of natural logarithm,  $b$  is the regression coefficient for  $T$  and  $c$  is the constant in the regression equation.

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# **Chapter 3: Cost Saving and Energy Saving under the Use of HEMS**

## **3.1 Introduction**

The challenge of modern society is to save energy and to use energy in an effective way for sustainable energy use. In one hand, high energy use for modern appliances is increasing the scarcity of energy for our future generation and in other hand it has been degrading the environmental quality. Most of the countries especially developed countries including Japan are being conscious about energy saving and energy management.

Systems like BEMS (Building Energy Management Systems), FEMS (Factory management Systems) etc. have been created for energy management. Home Energy Management System (HEMS) is one of the energy management systems that have been practiced in residential houses in different regions. Among all other energy management systems HEMS is so called effective energy management systems. HEMS is a visualization of the energy usage by connecting the electrical equipment in the home. It is a system to holistically control smart home appliances by computers through various multi-purposed HEMS apps and is connected with each other through information network [1]

The global HEMS revenue market was 1.5 billion USD in 2013 which increased by 2.1 times by the end of 2015. It was expected to reach 4200 million USD by the end of 2017 [2]. HEMS is getting popular in the countries like North America, China, Japan, Australia and in other countries which are the highest energy users in the world [3]. Different companies have been providing their HEMS services and products all over the world. From the government to service providers, all are working effectively to make HEMS effective wherever it has been practiced.

The HEMS concept has entered to Japanese market since 2008 [2]. On 1st April 2011, KDDI, Sharp and many other Japanese electrical companies made an alliance in order to rapidly lunch HEMS businesses. In September 19, 2012, Energy and Environment Council Japan articulated HEMS policy. From 2008 to 2020 the growth rate of HEMS and BEMS has been estimated to increase by 48%. The government of Japan aims to

set up HEMS to all of the new dwelling by 2030 [4]. HEMS have gained the support of Japanese government, including the issuing of subsidies, following the earthquake of 2011. As of 2015, it is estimated that twenty thousand HEMS have been introduced to individual homes in Japan [5]. The result shows that more people were found cooperative towards energy saving in the HEMS buildings [6].

It is obvious that HEMS is one of the important and effective tools for energy saving and to maintain indoor environment as all the electrical devices that have been used indoor and connected with the systems can be controlled. But the results [7-12] showed that the amount of energy saving from HEMS is not same in different areas.

Different journal papers [11-15], conference papers are reviewed and the data are collected from their results to understand energy saving and cost saving in different regions including Japan while using HEMS. The mean cost saving percentage was taken, if the cost saving percentage was between two ranges and overall percentage of energy saving and cost saving was calculated. The researches have been conducted in different areas and in different seasons with short term and long studies. The achieved savings decrease over time. Some studies have been conducted in different modes. The mean cost saving percentage was taken if the cost saving percentage was between two ranges and overall percentage of energy saving and cost saving was calculated. Our study shows mean cost saving of 7.9% is possible with the use of HEMS systems as shown in Figure 3.1.

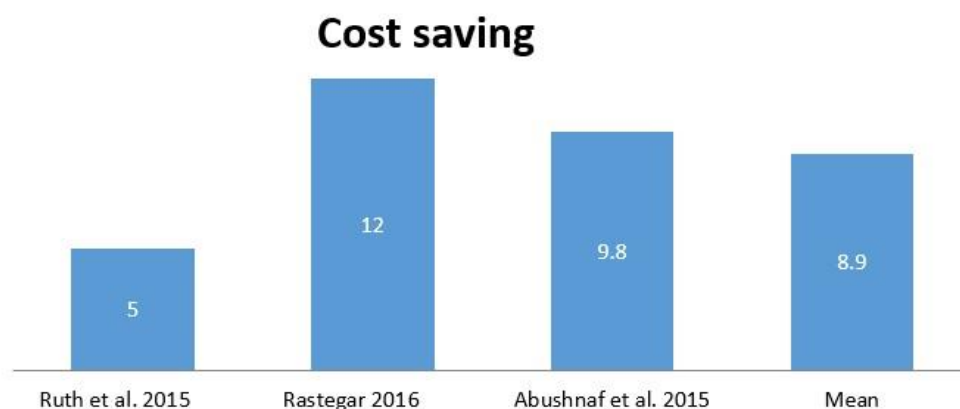


Figure 3.1 Cost saving under the use of HEMS systems

Similarly, our result also shows that mean energy saving of 16.3% is possible with the use of HEMS systems as shown in Figure 3.2. The result also showed that both the cost saving and energy saving results were due to various activities carried out. So far, the overall theme of these results was the importance of behavioral activities.

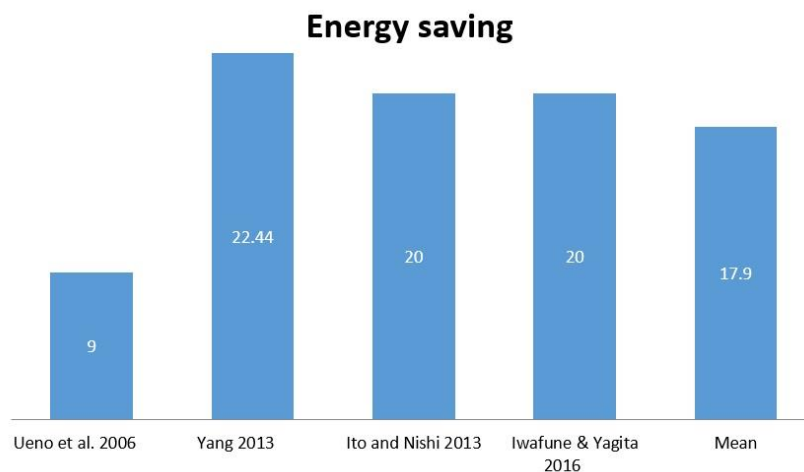


Figure 3.2 Energy saving under the use of HEMS systems

### ***3.2 Adaptive activities for cost saving and energy saving***

The effectiveness of HEMS has been evaluated by many researchers but most of the research pointed out the usefulness of HEMS. The behavioral and psychological side of HEMS users has been ignored in most of the researches. The energy saving percentage of HEMS varies in different places [11, 12, 14, 15]. It is the concern of all of us to understand the reason of this energy saving percentage variation. Some researchers found that HEMS are less effective. Recently, research has started to explore not only the saving but also the role that the design of HEMS has on their effectiveness and their ability to effectuate behavior change.

Very few studies have focused the behavioral influence in HEMS. They have pointed out how the behaviors of the users have affected the HEMS but they have not mentioned the solutions. The global adoption and implementation of energy management technology, the coherent and steady involvement of consumers is

required for the successful use of available technology. The changing behaviors of the consumers are always the challenge for the proper implementation of HEMS.

Table 3.1 shows that different researches found the amount of energy-saving and cost-saving differently. The reason for energy saving and cost saving variation in Table 3.1 is important to be analyzed for the effectiveness of HEMS in coming days and to bring the uniformity in the percentage of energy-saving and cost-saving. But the behavioral factors of the users in different regions including Japan while using HEMS made these differences. The reason for energy saving and cost saving variation in Table 3.1 is important to be analyzed for the effectiveness of HEMS in coming days and to bring the uniformity in the percentage of energy-saving and cost-saving. The researches have been conducted in different areas and in different seasons with short term and long studies. The achieved energy and cost savings increase or decrease over time. Some studies have been conducted in different modes. But the behavioral factors of the users were noticed as the main cause of energy saving variation.

To support the extension of electricity monitoring and effective implementation of HEMS, convincing design models should be created to target major factors which would appeal to consumers towards saving money and environmental impacts. With the visualization of the energy use some occupants feel empowered to take action to reduce their energy use with an increased sense of control given the knowledge of their usage. Other users feel despondent and fatalistic that their contribution was futile in the larger social and environmental contexts.

This fact implies that having users, saving electricity usage and sustainable energy reduced level may not be in linear relationship. Some special measures should be taken for the effectiveness and sustainable energy reduction. Most of the smart home users prefer smart thermostats for controlling the energy use. Smart plugs and lighting controllers are another major HEMS control products which are expected to account for a substantial market growth. These devices are driving the overall HEMS hardware market and in turn spurring the market growth. The

following measures might be required to encourage the sustainable, preventive behaviors of energy reduce.

1. Human behaviors should be influenced to increase the interest in such an energy visualization system so that the users determine for energy reduction and adopt different behaviors for energy saving.
2. The concern to environmental issues and normal electricity usage should be increased. Generally, people are less concerned to environmental issues and participating less in normal electricity use activities. It is important to increase the people's participation for environment related activities so that they could understand how excessive use of electricity is degrading the environment.
3. The technical aspects of HEMS devices deployment and implementation should be made accessible to common people. The users may not use the provided system due to lack of the knowledge like handling the devices. So the technical knowledge of using the system and handling the devices should be focused. The service provider should focus to provide the information in an easy way.

One of the essential topics with energy management is thermal comfort. Thermal comfort is the satisfaction of the mind with thermal environment. As people use different electrical appliances to increase the comfort. How thermal comfort can be maintained with less energy use is important to be analyzed. The knowledge of adaptive behaviors that people do to maintain thermal comfort with less energy use might be useful for better energy management in the future. Generally, using HEMS, the excessive use and the waste can be easily seen, it helps people to manage the power saving. By HEMS device the indoor temperature can be controlled so it is also a better tool for creating comfortable indoor environment and adjust the thermal comfort. But there are few researches done to understand the thermal comfort level of the occupants with HEMS management. Occupants' behavior is different according to the places. It is important to understand the thermal comfort level of the occupants especially when they are living in the smart houses for proper management of smart houses in coming days.

Our objectives in this paper are to review energy saving and cost saving under HEMS and to discuss the activities carried out for energy saving and cost saving during HEMS use. We will also observe the thermal comfort level and the occupants' behaviors of the HEMS managed buildings. Our results might be fruitful to the building designers to design more comfortable homes and HEMS service providers to make HEMS more effective in the days to come.

Table 3.1 Behavioral activities under the use of HEMS

No	References	Place of study / Studied samples/ Studied period	Method / Concept	Energy saving (%)	Cost saving (%)	Identified activities for energy and cost saving	Remarks
(1)	Ueno et al. 2006 [10]	Japan / 9 residential houses / 2 months	Household survey / Energy Consumption Information System (ECOIS) was developed to display the power use.	9	-	1) Energy saving activity such as change in the use of heating appliances was carried out. 2) Due to awareness provided the pattern of television use was changed. They were conscious to power off when not in use. 3) Refrigeration capabilities were adjusted. The disconnection of the appliances was increased when not in use. 4) The hours of keeping warm the rice cooker after boiling rice was reduced.	City gas and kerosene consumption for heating was not measured.
(2)	Yang 2013 [11]	Taiwan / 8 months	Experiment method / Web-service-based Information Agent System (WIAS) was developed and the consumers can easily get the complicated information service as well as the tips to change the behaviors like "Change the light, change the behavior", " Don't leave things turned on".	22.44	-	1) The devices are automatically controlled, the sensors laid out decides whether air conditioning should operate fan or compressor. If the temperature is over 28 °C, the compressor turns on. If the humidity or CO2 increased compressor turn off and fan turn on. 2) If the lighting value is high, the lights would be turned off one by one around the outer circle.	Automatic device control system was noticed as one of the efficient way to reduce energy because the energy saving is high.
(3)	Ito and Nishi 2013 [12]	Japan / A typical house in Japan / 5 days in November	Experiment and observation method / HEMS was installed	20	-	Real time management for HVAC control reduces power use without interfering with environmental amenity.	-
(4)	Iwafune & Yagita 2016 [9]	Japan / 532 detached houses and 208 apartment types houses / 1 year	Household survey / Household characteristics on electricity consumption	20	-	1) Use of electric central air conditioning for heating and cooling was noticed as the main cause of high electricity consumption so non electric space heating used to reduce the energy. 2) Use of LED light also reduced electricity than incandescent or fluorescent lamps.	-
(5)	Ruth et al. 2015 [5]	US (southeast) / 20 well insulated houses / 1 month (summer)	Simulation method	-	5	Power use time has been shifted from peak hours to less expensive times so that the house can be pre-cooled before peak electricity price.	The electricity expenses varied because of variations in desired temperature and their profiles between homes.
(6)	Rastegar 2016 [13]	Canada / Users, customers and utility company	Interaction method / A price based HEM framework is designed. 2 cases are determined and mathematical optimization models are used.	-	12	1) Appliances are categorized into controllable and uncontrollable and the consumption level of these appliances is controlled. 2) The lower limit use of the devices was focused. 3) The plug-in hybrid electric vehicle (PHEV) batteries are charged in low tariff time and discharged at high tariff time.	Period of study is not mentioned.
(7)	Abushnaf et al. 2015 [14]	Australia / Residential hourly loads data collected by National Energy Modeling System / 1 year	Simulation method / Demand Response (DR) program is used to simulate the energy use reduction minimizing inconvenience to the consumption.	-	9.8*	The system decides the request to run appliances according to the priorities. Once the priority is listed HEMS decides to shift the time of use or switch off certain appliances.	-
<b>Overall Mean Saving</b>				<b>17.9</b>	<b>8.9</b>		

### **3.3 Conclusions**

A preliminary factor for the successful implementation of smart grid technology is changing consumer behavior towards adopting smart grid technology and leveraging it to its full potential. Some measures can be taken to bring uniformity in the way of electricity use and change the behaviors towards energy saving. Some systems can be designed to provide appropriate appliance operations according to priorities learned from the users' lifestyle. Electricity is used by all people from different demographic. Especially, it is regulated and operated by adults in homes as well as in commercial areas. So, adult from one home should be taken as target consumer including HEMS users. Special policy from the government as well as concern authorities should be applied to involve every target in the activities about providing technological knowledge and environmental knowledge so that they could deliver that knowledge to other members of the homes.

In many researches, it was found that users tend to ignore energy monitoring after certain period. Some apps can be added with energy management software that could attract or motivate people towards regular use of the technology. For example, if some health related apps are included which could help the users to remain healthy and fit, they could use it regularly. Users liked apps that provided convenient tools, including feedback, to help them monitor, track and review attempts to change or improve health behavior. So HEMS should be developed into adoptive technology which would lead the sustainable behaviors of the users towards energy saving. Then only, HEMS use seems to be uniformly. From the review of the previous researches done on the HEMS and energy management, the present status of global HEMS market and the increasing scope of HEMS globally and in Japan were observed and also the thermal comfort level of HEMS-managed residential buildings located in Tokyo Japan was identified. We obtained the following result from this study;

1. It has been understood that energy saving and cost saving is possible with the use of HEMS in buildings. In HEMS buildings so far 17.9 % of energy saving and 8.9% of cost saving is possible if it is effectively applied.
2. HEMS developed so far is not strong enough to focus the behaviors of the occupants so that there is not uniformity in energy saving between the HEMS users. Some apps related to the behaviors should be included with HEMS in the future.

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# **Chapter 4: Thermal Environment of HEMS Managed Building**

## **4.1 Introduction**

Thermal environment consists of air temperature, relative humidity, air velocity, radiant temperature, and metabolic rate. These factors are interrelated and are the main parameters affecting indoor thermal environment. Occupants living in any types of dwelling have an opportunity to create suitable indoor thermal environment [1, 2] Generally, it is believed that indoor environment can be improved only with the use of heating and cooling. But there are other alternative ways to improve indoor thermal environment and to adjust thermal comfort. Window opening is one of the ways to improve indoor thermal environment in summer and clothing adjustment is one of the way to improve thermal comfort in winter. Generally, when you live smart life, you imagine a different environment than a common living. The use of HEMS system enables the users to alter the way of indoor devices use. With the use of HEMS, the indoor electrical devices are easily controlled so what types of indoor thermal environment is created with HEMS use is not studied yet. We further discuss the indoor thermal environment during HEMS use in other sections.

## **4.2 Air temperature**

Air temperature is a measurement of how hot or cold the air around us is. It is the most commonly measured parameter thermal environment. More specifically, temperature describes the kinetic energy or motion of the energy of the gases that make up air. If gas molecules move more quickly, air temperature rises. Air temperature also affects nearly all other weather parameters. So it is considered as one of the most important parameters of thermal environment.

### **4.2.1 Monthly air temperature**

The relationship between monthly mean indoor and outdoor air temperatures was investigated to understand how the indoor air temperature fluctuated corresponding to outdoor air temperature. As shown in Figure 4.1, the fluctuation trend of indoor air temperature is quite similar to that of outdoor air temperature but the amplitude is smaller. Realized indoor air temperature is different from one month to another. The

difference between indoor and outdoor air temperature is large in January and small in August. The indoor air temperature is almost 20°C for the months with monthly outdoor air temperature below 10°C; that is, in January, February and March. The highly insulating materials used in the building is one of the causes of this temperature difference besides heating use, because similar trend is observed even with those flats of no heating use i.e. FR mode. The result showed that the indoor temperature was changing by months. Similar result has been obtained from the study done in residential buildings in China and UK [3-5]

The indoor air temperature variation has also been observed with the modes. The modes (HT, CL and FR) are determined on the basis of the use of heating, cooling and free running of heating and cooling devices. The FR mode is for the condition while the occupants were not using any appliances of heating and cooling. Figure 4 shows the monthly average indoor temperature variation at all in the whole year for each mode. The indoor air temperature changes with the months and it seems to be affected by outdoor environment. We can see the shape of normal variation in the indoor air temperature distribution in FR mode. The lowest air temperature appears in winter months and the highest in summer months. The occupants started using cooling devices from May. The highest temperature in a raw data was observed at the end of August in CL mode. In winter, the occupants seem to have maintained the temperature above 20°C in HT mode.

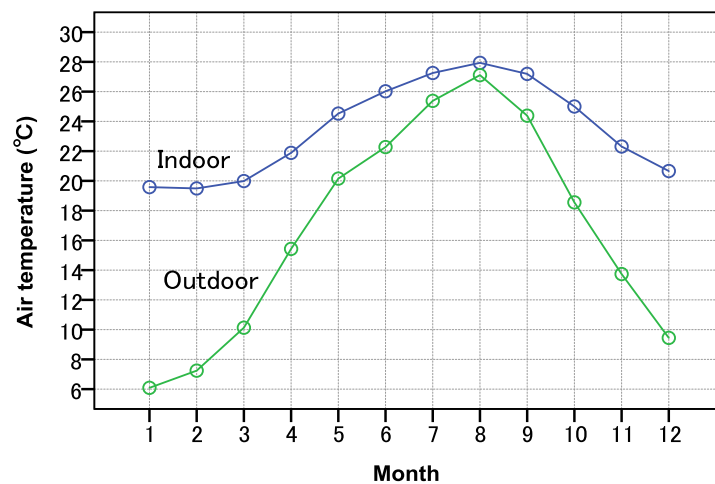


Figure 4.1 Monthly relation between indoor and outdoor air temperature

#### 4.2.2 Indoor air and its relation to outdoor air temperature in different modes

Figure 4.2 shows the relation between indoor and outdoor air temperature in different operating modes for the whole year. In FR mode, the indoor air temperature is highly correlated with outdoor air temperature.

The regression equations are given below.

$$\text{FR mode } T_i = 0.408 T_o + 18.3 \quad (n = 6725, R^2 = 0.75, \text{S.E.} = 0.003, p < 0.001) \quad (4.1)$$

$$\text{CL mode } T_i = 0.120 T_o + 26.4 \quad (n = 744, R^2 = 0.12, \text{S.E.} = 0.012, p < 0.001) \quad (4.2)$$

$$\text{HT mode } T_i = 0.186 T_o + 20.0 \quad (n = 4024, R^2 = 0.13, \text{S.E.} = 0.007, p < 0.001) \quad (4.3)$$

Where,  $T_i$  is indoor air temperature (°C);  $T_o$  is outdoor air temperature (°C);  $n$  is number of votes;  $R^2$  is the coefficient of determination; S.E. is standard error of the regression coefficient and  $p$  is the level of significance for the regression coefficient.

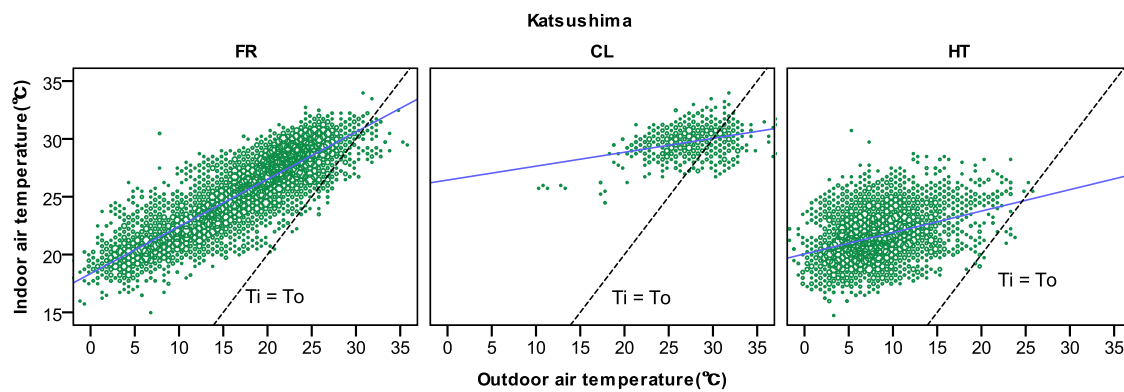


Figure 4.2 Mode wise indoor and outdoor air temperature: (a) Monthly mean and (b)

Relation of indoor and outdoor air temperature

The correlation coefficient for FR mode is higher than CL and HT mode. It is probably due to heating and cooling use. As shown in Table 4.1, the regression coefficient of this study is slightly less than the study done in Tokyo and Yokohama in all FR, CL and HT modes [6]. The ordinary houses of Tokyo and Yokohama area do not have very good insulation compare to this study so the heat transfer from inside the house to the outside environment is high compare to this condominium. Compare to the studies done in Tokyo, Kanagawa and Chiba [6] and Kanto region [7], this condominium has less

influence of outdoor temperature in indoor temperature. The reason is this condominium has been newly constructed and good insulating materials were used compare to other ordinary houses. Table 4.1 shows the comparison of regression equations of this study with other studies in Tokyo and Yokohama areas in Japan.

Table 4.1 Comparison with other studies

References	Types of house	Mode	Season	Areas	Equations
This study	HEMS condominium	MM	Winter	Tokyo	$T_i = 0.196 T_o + 20.2$
This study	HEMS condominium	MM	Spring	Tokyo	$T_i = 0.334 T_o + 19$
This study	HEMS condominium	MM	Autumn	Tokyo	$T_i = 0.391 T_o + 19.74$
This study	HEMS condominium	MM	Summer	Tokyo	$T_i = 0.236 T_o + 23.6$
Katsuno et al. (2012) [8]	Ordinary house	CL	Summer	Tokyo/Yokohama	$T_i = 0.149 T_o + 23.66$
Katsuno et al. (2012)	Ordinary house	FR	Summer	Tokyo/Yokohama	$T_i = 0.521 T_o + 14.8$
Imagawa et al. (2015) [9]	Ordinary house	FR	All	Tokyo, Kanagawa, Chiba	$T_i = 0.727 T_o + 9.4$
Imagawa et al. (2015)	Ordinary house	CL	All	Tokyo, Kanagawa, Chiba	$T_i = 0.257 T_o + 20.3$
Imagawa et al. (2015)	Ordinary house	HT	All	Tokyo, Kanagawa, Chiba	$T_i = 0.327 T_o + 14.0$
Rijal H.B. (2014) [7]	Ordinary house	FR	All	Kanto region	$T_i = 0.587 T_o + 12.6$
Rijal H.B. (2014)	Ordinary house	CL	All	Kanto region	$T_i = 0.183 T_o + 22.3$
Rijal H.B. (2014)	Ordinary house	HT	All	Kanto region	$T_i = 0.220 T_o + 17.4$

The regression coefficient of this study for winter is lower to others in HT modes. Similarly, the regression coefficient of this study for summer is also lower than other similar types of the studies done in ordinary buildings. The reason might be the effect of heat capacity enhanced by the use of the highly insulating materials in this building than other buildings, which were mainly detached houses.

#### 4.2.3 Seasonal air temperature

Figure 4.3 shows the relationship between indoor and outdoor air temperatures in respective four different seasons. The indoor air temperature in spring and autumn seasons tend to be highly correlated to the outdoor air temperature. In winter season, the indoor and outdoor air temperature difference is quite large; the indoor air temperature is much higher than outdoor air temperature. It is due to the highly insulating materials used in the building along with the use of heating. In summer, the difference between indoor and outdoor air temperature is quite small which shows that the cooling use is not so large or the occupants' might have used high temperature setting. The linear regression equations are as follows:

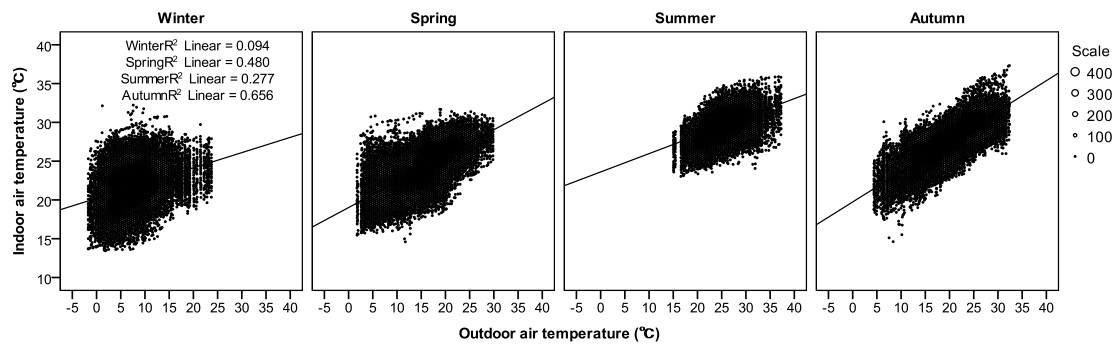


Figure 4.3 Seasonal indoor air temperature

$$\text{All } T_i = 0.377 T_o + 17.218 (n=1047900, R^2=0.72, \text{S.E.}=0.008, p<0.001) \quad (4.4)$$

$$\text{Winter } T_i = 0.196 T_o + 20.21 (n=78775, R^2=0.09, \text{S.E.}=0.002, p<0.001) \quad (4.5)$$

$$\text{Spring } T_i = 0.334 T_o + 19.02 (n=82112, R^2=0.48, \text{S.E.}=0.001, p<0.001) \quad (4.6)$$

$$\text{Summer } T_i = 0.236 T_o + 23.61 (n=804062, R^2=0.28, \text{S.E.}=0.001, p<0.001) \quad (4.7)$$

$$\text{Autumn } T_i = 0.391 T_o + 19.74 (n=82951, R^2=0.66, \text{S.E.}=0.001, p<0.001) \quad (4.8)$$

where,  $T_i$  is indoor air temperature (°C);  $T_o$  is outdoor air temperature (°C);  $n$  is number of votes;  $R^2$  is the coefficient of determination; S.E. is standard error of the regression coefficient and  $p$  is the level of significance for the regression coefficient.

The seasonal mean of the indoor air temperature is calculated to understand the influence of seasonal change in indoor thermal environment. We found differences in the mean seasonal indoor air temperature in the studied building as shown in Figure 4.4. The mean air temperature is 29.6°C in summer and 21.9 °C in winter; both are slightly higher than the recommended temperature values in Japan, 20°C for winter and 28°C for summer. The autumn mean air temperature is 2.3°C lower than summer and 3.1°C higher than spring seasons.

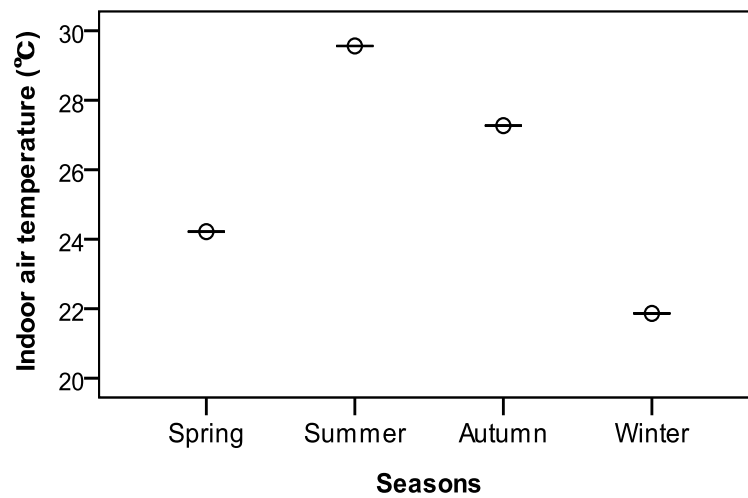


Figure 4.4 Seasonal mean indoor air temperature

#### 4.2.4 Relation of temperature setting and indoor air temperature

The indoor air temperature is also compared with temperature setting to understand how the occupants set heating and cooling point to adjust the indoor air temperature. As shown in Figure 4.5, the indoor air temperature is different than temperature setting. There is noticeable difference between indoor air temperature and temperature setting in HT and CL mode. In HT mode, the indoor air temperature is lower than temperature setting. The reason might be the effect of low outdoor air temperature. But in CL mode, the indoor air temperature is higher than temperature setting. The reason might be the effect of solar radiation. The use of shading might be useful to reduce the indoor air temperature during very hot period.

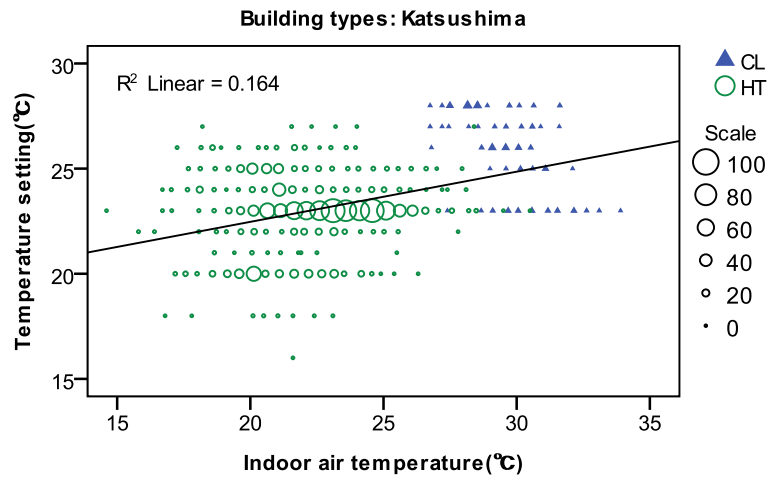


Figure 4.5 Temperature setting and indoor air temperature

#### 4.2.5 One-day variation of indoor air temperature

In order to understand the indoor air temperature variation of different families, we observed one-day indoor air temperature variation of different flats of summer and winter seasons. Figure 4.6 shows the indoor air temperature variation of the studied flats in the month of January.

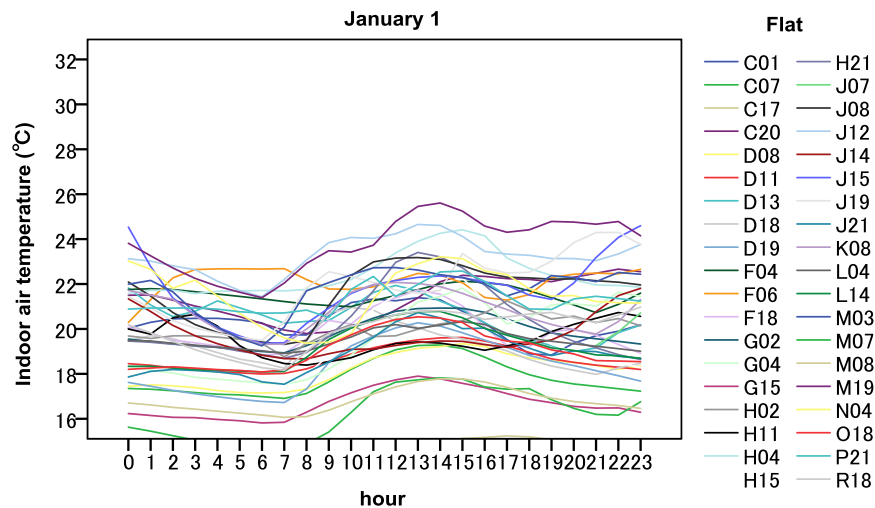


Figure 4.6 One-day air temperature variation in the month of January



There is almost 10°C difference between the flats maintaining the highest and the lowest temperature. The result showed that the temperature decreased in the morning time. The temperature gradually increased in day time and again decreased in the evening time. At 20:00 pm onward, the indoor air temperature increased again due to heating use. The occupants were observed using heating in the evening time only. The heating use is done till 12 am.

Figure 4.7 shows one-day indoor air temperature variation of the studied flats in August. The cooling use is not strongly used except some flats because the fluctuation of the temperature is not very sharp.

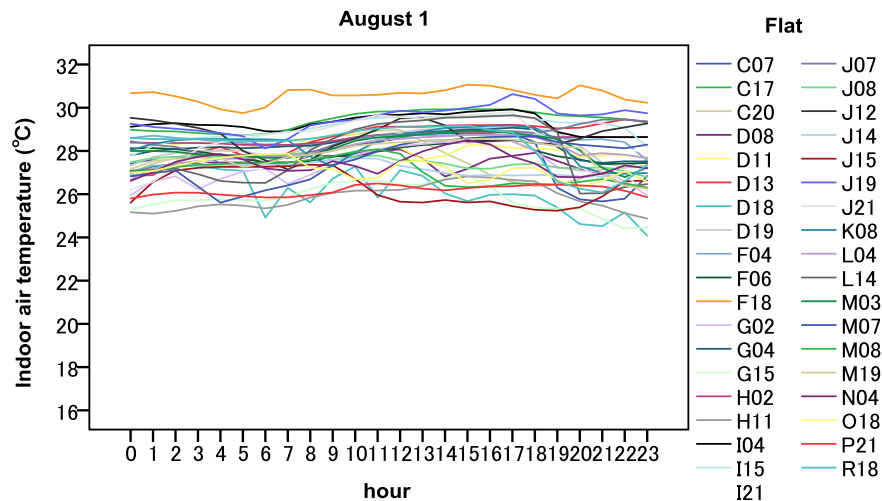


Figure 4.7 One-day air temperature variation in the month of August

The result showed that there is almost 6°C temperature difference between the flats maintaining the highest and the lowest temperature. At 20:00 pm onward, the indoor air temperature seems slightly decreased due to the use of cooling.

#### 4.2.6 Monthly variation of indoor air temperature in different seasons

We observed the mean indoor air temperature of four months representing to all seasons according to the floors. Table 4.2 shows the number of data of four representative months of four seasons. We observed the monthly mean indoor air temperature of January, April, August and October for winter, spring, summer and autumn respectively.

Table 4.2 The number of data of representative four seasonal months per floor

Floor	N (January)	N (April)	N (August)	N (October)
3	2544	2518	2671	3146
4	3720	3593	3605	5153
6	2176	1942	2195	2535
7	2232	2160	2232	2407
8	1378	1259	1196	1714
9	1763	2160	2232	2570
10	5095	4687	5168	5821
11	744	720	744	1247
12	1476	1440	1487	2231
13	2916	2880	2976	3974
14	744	720	744	744
15	745	708	744	936
16	744	720	744	744
18	744	720	744	759

As shown in Figure 4.8, the result showed that the mean indoor air temperature ranged from 19°C to 31.5°C in different seasonal months in different floors. The indoor air temperature fluctuation of the floors is large in January (Figure 4.8a) and small in August (Figure 4.8c). The variation of indoor air temperature in April (Figure 4.8b) and October (Figure 4.8d) is not like January and August but the amplitude is not large than January. The seasonal change of indoor air temperature does not necessarily look consistent with each other. For example, the indoor air temperature of floor 15 has the highest temperature among all the floors in January, but floor 9 has the highest temperature among all the floors in August. This suggests that the indoor environment has been influenced by the occupants' behaviors rather than the floor difference of floor level in the studied condominium.

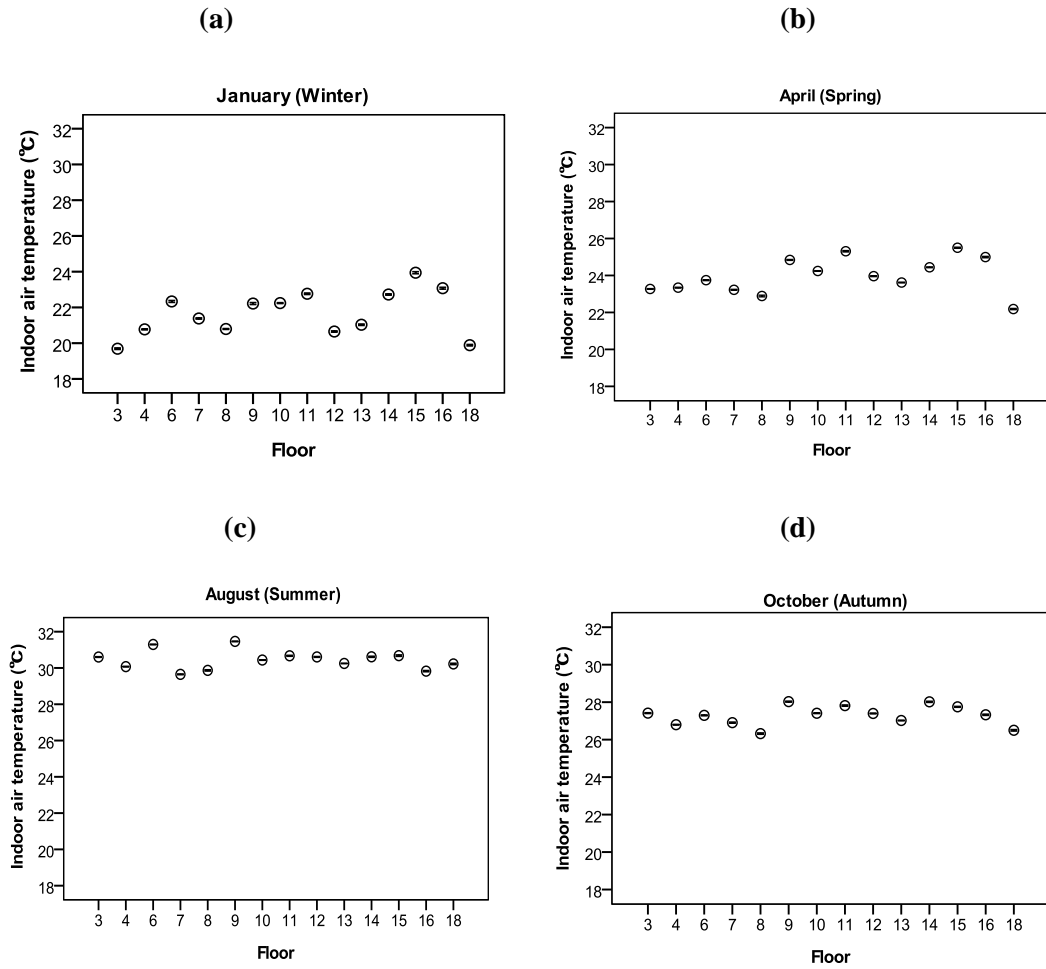


Figure 4.8 Monthly indoor air temperatures of different seasons

#### 4.2.7 Flat wise air temperature

The indoor air temperature variation of all the flats was analyzed from the measured data to know whether the indoor environment is maintained similar or different by different families. As the building is HEMS managed so we generally guess similar indoor thermal environment in all the flats. Figure 4.9 shows that the individual behaviors of each family has resulted difference in indoor air temperature. The mean indoor air temperature is 19.9°C which is quite similar to the study done in English homes [9] which is 19.5°C. The mean indoor air temperature in summer is 27.1°C. There is almost 12°C difference in temperature range among the flats in winter and almost 6°C difference in summer. The indoor air temperature in summer is observed

high for most of the flats which proved that the use of mechanical cooling was not large. We will discuss about the proportion of mechanical heating and cooling use is next section.

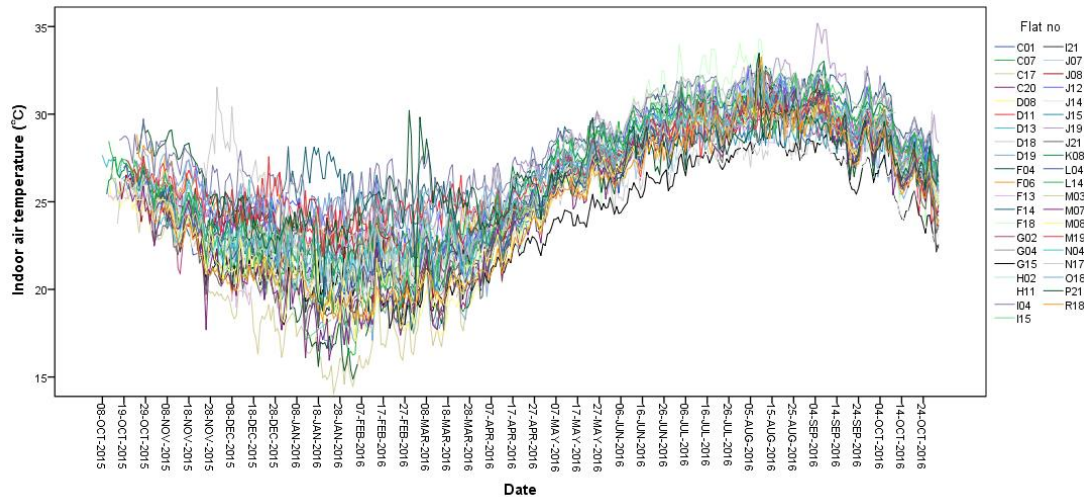


Figure 4.9 Indoor air temperature of different flats

We analyzed the indoor and outdoor air temperature of those flats who voted regularly for the whole year in FR mode during summer and winter and then in CL and HT modes.

Table 4.3 Flat code with their location and area

Flat No.	Location	Type	Area (m <sup>2</sup> )
C15	Centre	3LDK	75.74
C01	South corner	3LDK	77.13
C04, F04, F13, G04, J02, L03, M04	Centre	3LDK	71.01
C07, J07	Centre	3LDK	73.39
D05	Centre	3LDK	72.03
D11, E12, H11, J12, J14, L11	Centre	3LDK	74.20
E18, R18	Centre	3LDK	75.74
J08, M08	Centre	4LDK	90.23
Q14	Centre	3LDK	73.39
G21, P21, Q21	North corner	3LDK	74.20
LDK : Living, Dining & Kitchen			

Some flats with very low number of data in FR mode during summer and winter were not included. The studied flats with their areas and location in the building are mentioned in Table 4.3. The area of the studied floor ranged from 71.01 to 90.23m<sup>2</sup>. There were four flats lying at the corner side and 22 lying at the center part of the studied condominium.

As shown in Figure 4.10, the indoor air temperature is quite consistent to outdoor air temperature in summer and winter in FR mode. The indoor air temperature is higher than outdoor air temperature. The mean indoor air temperature is 29°C which is quite close to outdoor air temperature in summer. In winter the mean indoor air temperature is 21.2°C whereas the mean outdoor air temperature is 8.2°C. This difference between indoor and outdoor air temperature in FR mode in winter is due to high insulated building which gained internal heat from different sources inside in the studied flats.

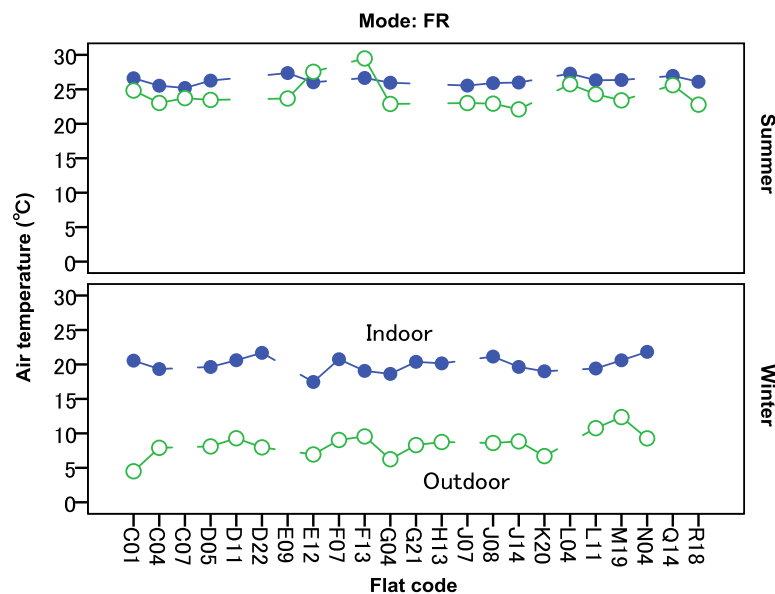


Figure 4.10 The relation of indoor and outdoor air temperature in summer and winter in FR mode

As shown in Figure 4.11, the mean indoor and outdoor air temperature of 26 families in HT and CL modes are compared with the corresponding mean outdoor air temperature in order to know the trend of indoor temperature fluctuation and to find out to what extent it is influenced by outdoor temperature or not. The indoor air temperature always different according to families. The difference between indoor air temperature from one

family to another and outdoor air temperature in CL mode is within the range of 25 to 30°C. In HT mode, the difference between indoor air temperature and outdoor air temperature is large. Most of the families have maintained the indoor air temperature above 20°C while the outdoor air temperature was below 15°C. Comparatively, the flats C01 and P21 which are located at the corner have lower temperature than the flats located at the center of the building in all the modes. It might be due to the flats at the corner lost heat from more sides than the flats located at the center of the building. In HT mode the indoor air temperature obvious but in CL mode the indoor air temperature is high. We will discuss about the adaptive behaviors of the occupants carried out for thermal comfort in terms of this high temperature in other section.

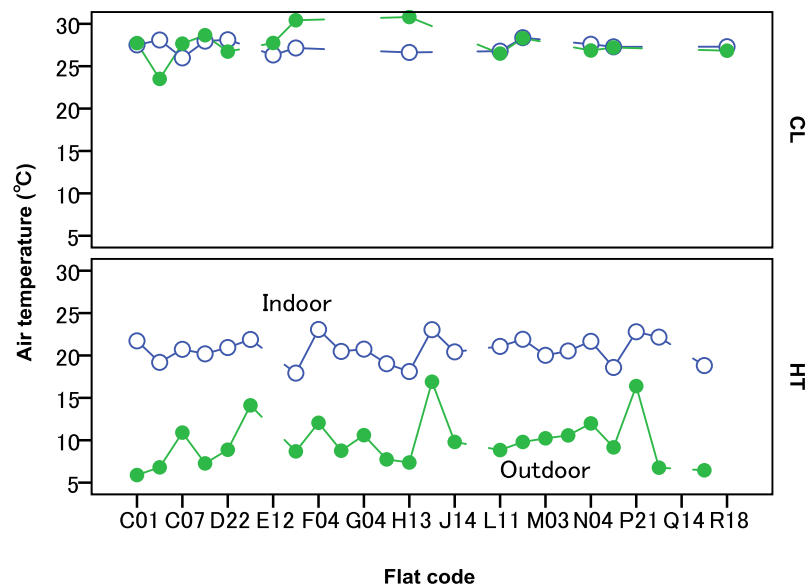


Figure 4.11 The relation of indoor and outdoor air temperature in CL and HT modes

#### 4.2.8 Location wise air temperature

The mean indoor air temperatures with 95% confidence interval (Mean  $\pm$ 2 S.E.) in two different positions (center and corner) were analyzed from the measured data according to seasons. Figure 4.12 shows that the location of the flat in the building has influenced the indoor air temperature in different seasons. Flats at the center have higher air temperature than the flats at the corner. The studied building has the south main

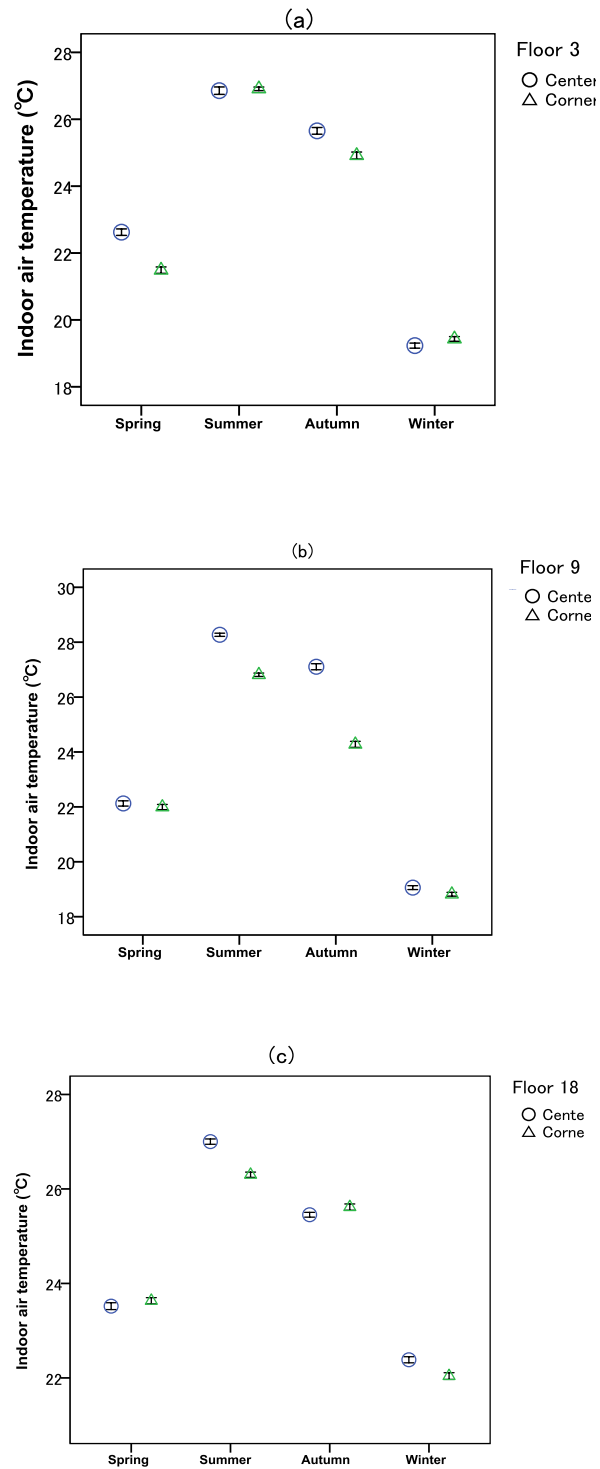


Figure 4.12 Seasonal differences of indoor air temperature of flats of different floor on corner or center; (a) 3<sup>rd</sup> floor (b) 9<sup>th</sup> floor and (c) 18<sup>th</sup> floor

orientation so the flats in the center loose heat from north and south sides only, but the flats located at the corner loose heat from three sides including east side for east corner flats and west side for west corner flats. The mean temperature difference between center flat and corner flat is large in spring and autumn than summer and winter. It is due to heating and cooling use. In Spring and autumn, the occupants do not use heating and cooling so there is temperature difference due to differences in heat loss. The corner flat lost more heat than the flats at the center. But in summer and winter the mean temperature difference is less because both the flats of corner and center used heating and cooling more or less. Figure 4.12a shows the mean seasonal air temperature difference in 3<sup>rd</sup> floor. There is almost 1.5°C difference between center flat and corner flat in spring and autumn. But the difference is less in summer and winter. Figure 4.12b shows the mean seasonal air temperature difference in 9<sup>th</sup> floor. There is almost 2°C difference between center flat and corner flat in summer and autumn. But the difference is less in spring and winter. Figure 4.12c shows the mean seasonal air temperature difference in 18<sup>th</sup> floor. There is small difference between center flat and corner flat. It is due to the newly constructed building and highly insulation materials used. In summer and winter the center flat has the higher temperature than corner but in spring and autumn the center flat has the lower temperature than corner flat. But the difference is less in summer and winter

#### **4.2.9 Day time and night time air temperature**

Night time and daytime air temperature is observed to find out to what extent night temperature varies than day time temperature. It is obvious that the occupants will be at home at night if they go for work in daytime. Generally, it is expected that heating and cooling use at night time might make the indoor air temperature different than day time. Figure 4.13 shows that there is no big difference in indoor air temperature between day time and night time in all the months except June, July and August. During these months, the night time temperature is slightly lower than day time temperature. There might be two reasons for this difference. One reason might be due to solar radiation; the daytime temperature is higher than night time temperature. The other reason might be due to the use of cooling. As the night time temperature is lower in summer months. So, the occupants might have used cooling due to high indoor temperature.



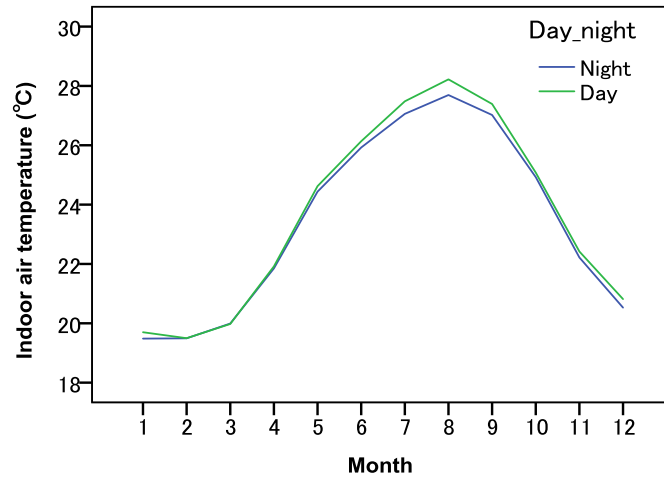


Figure 4.13 Monthly day-time and night-time air temperature

We further studied the four shift air temperature of morning time, afternoon time, evening time and sleeping time temperature. As shown in Figure 4.14,

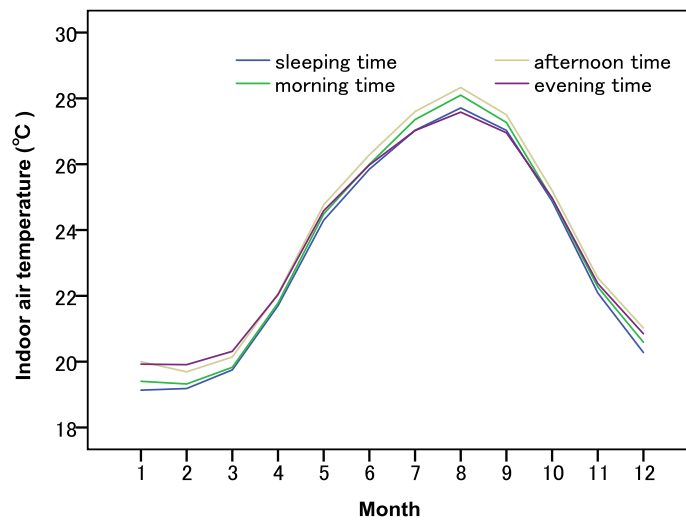


Figure 4.14 Indoor air temperature in different shifts of time.

we found the air temperature differences only in summer and winter time. The sleeping time temperature is highest in winter months (December, January and February). It is due to the use of heating. The afternoon temperature is the highest in summer months (June, July and August). It is due to high solar radiation. Comparatively, the sleeping time temperature is higher than sleeping time temperature. Possibly, the occupants

used cooling at sleeping time. They did not use cooling at the morning time because at morning time the outdoor air temperature decreases that might have help to lower the indoor air temperature.

#### 4.2.10 Air temperature variation on weekdays and weekends

The weekdays and weekends air temperature was observed for two winter and summer months according to floors. Figure 4.15 shows that the weekends temperature is higher than weekdays temperature in January. In weekdays, the occupants might have gone for work but in weekend they stayed at home. So, in weekends the heat generation is high due to the presence of people and due to other activities like cooking. The occupants might have used heating if the indoor air temperature went low.

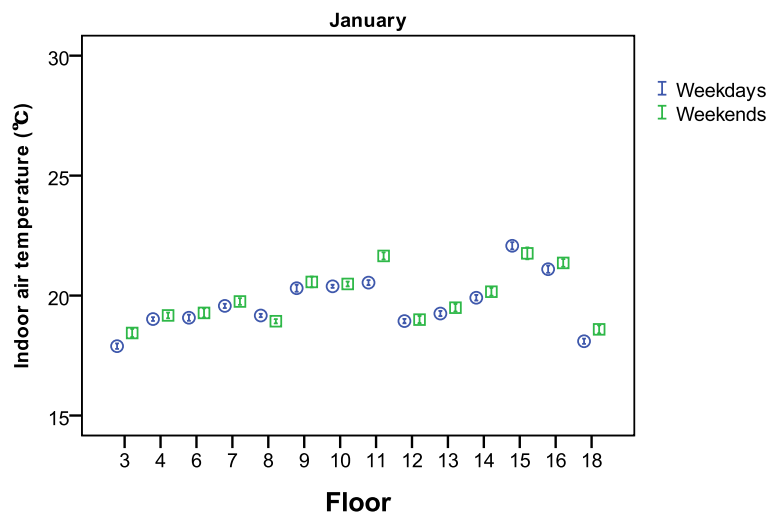


Figure 4.15 Weekdays and weekends air temperature in January

but in August weekend temperature is lower than weekdays temperature as shown in Figure 4.16. In weekends, the occupants might have been staying at home. They adapted various behaviors like window opening, fan use or they might have used cooling if the indoor air temperature was high that led the indoor air temperature decrease.

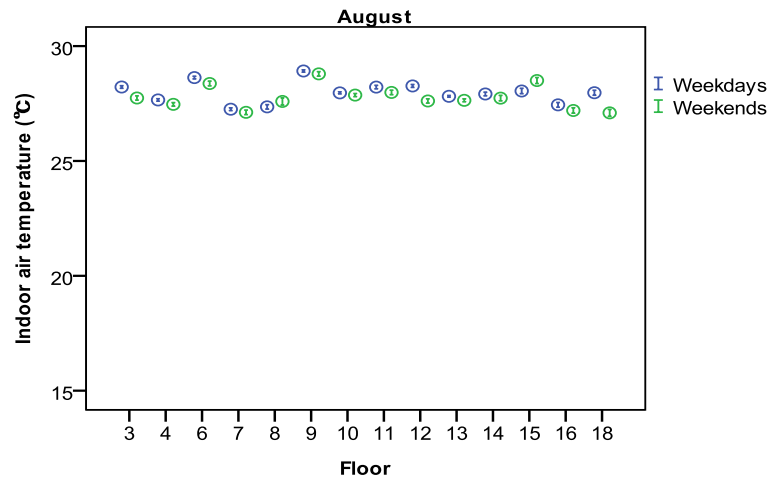


Figure 4.16 Air temperature on weekdays and weekends

#### 4.2.11 Two groups with higher and lower indoor air temperature

The indoor air temperatures were different according to the seasons, flats and floors. We wondered how the people adapted with this temperature differences and what are the behaviors people are taking for restoring thermal comfort. We listed only those flats with both measurement data and questionnaire data and divided them into four groups, SH (high temperature groups in summer) and SL (low temperature groups in summer), WH (high temperature group in winter) and WL (low temperature group in winter) on the basis of mean indoor air temperature. Figure 4.17 shows the number of data for these groups in FR and MM mode in summer and winter.

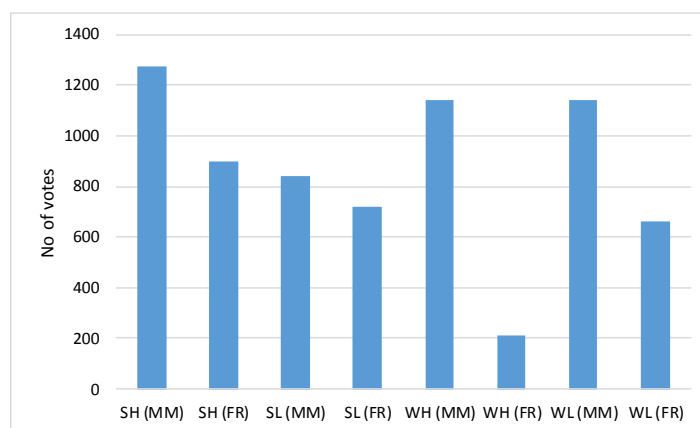


Figure 4.17 The number of votes for higher and lower temperature groups in different mode

Figure 4.18 shows mean indoor air temperature of these groups in summer and winter. The different between SH and SL is 1.8°C in CL mode 1.7°C in FR mode. This is due to individual difference cooling behaviors in CL mode. The temperature difference is FR mode is due to the difference in behaviors like window opening or door open. Similarly, there is 1°C difference in HT mode between WH and WL. Similarly, there is 2.6°C difference between WH and WL in winter. These temperature differences suggest that individual occupants' behaviors play a key role to determine the indoor thermal environment.

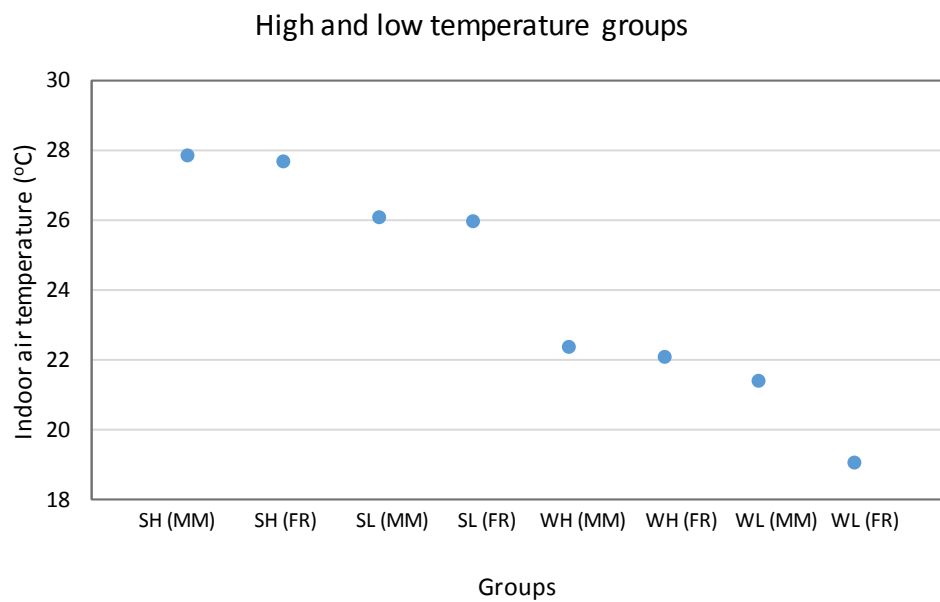


Figure 4.18 Mean indoor air temperature of higher and lower group in summer and winter

We also observed the cumulative percentage of the four groups for higher and lower indoor air temperature in summer and winter in MM mode. The cumulative percentage of the observed two groups shows the cumulative percentage the time spend with higher or lower temperature inside.

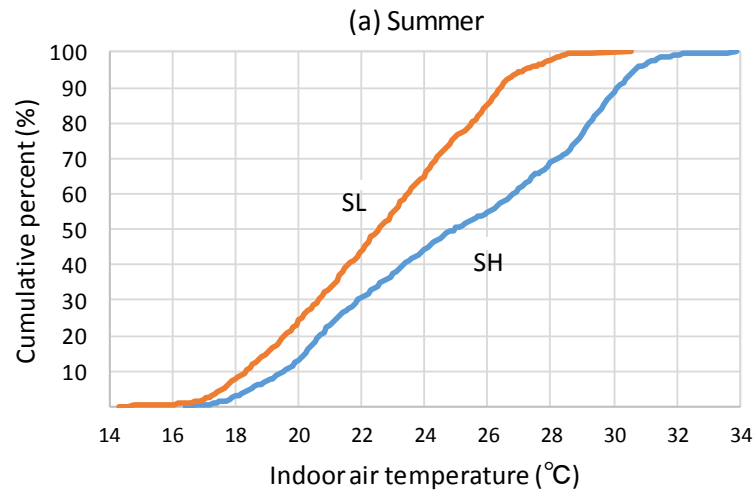


Figure 4.19 Cumulative percentage of air temperature for higher and lower temperature groups in summer

Figure 4.19 shows the cumulative percentage of both higher and lower indoor air temperature groups in summer and winter. In SL group, the number of time indoor air temperature being higher than 28°C is very small, while on the other hand, in SH group it almost 30%. We found 2°C difference in indoor air temperature between SH and SL.

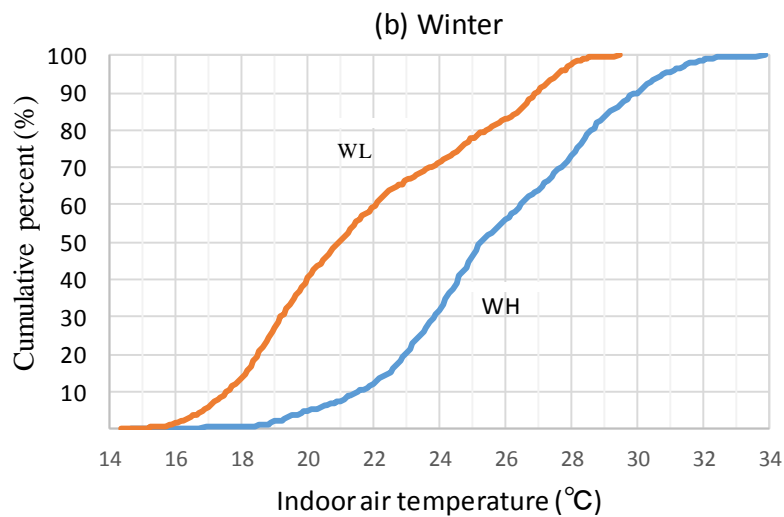


Figure 4.20 Indoor air temperature of higher and lower groups: (a) Summer and (b) Winter

Similarly, Figure 4.20 shows the cumulative percentage of the air temperature of higher and lower group in winter. In WL group, the number of time indoor air temperature being higher than 28°C is small but in WH group it is more than 30%. The indoor air temperature difference between WH and WL was almost 4°C.

### 4.3 Relative humidity

Table 4.4 shows the seasonal indoor air temperature and relative humidity in the studied year. The table showed around 7°C variation in indoor air temperature between the seasons. The relative humidity difference is up to 20% among the seasons

Table 4.4 Air temperature and relative humidity of four seasons

Seasons	N	$T_i$ (°C)	S.D.	$RH_i$ (%)	S.D.
Winter	471152	19.9	2.2	32.0	8.5
Spring	491249	22.1	2.5	41.5	9.2
Summer	481828	27.1	1.5	53.0	7.3
Autumn	495914	25.0	2.4	47.8	10.0

Figure 4.21 shows variations of monthly mean indoor and outdoor air temperatures, relative humidity and water vapor concentration for the whole year of the studied building. Mean values for the whole year are taken. The indoor air temperature swings moderately from a season to another season between 19°C and 28°C. This fluctuation is also different in different months. During January, February and March, the mean indoor temperature stays rather constant at around 19°C, though the outdoor air temperature decreased below 10°C.

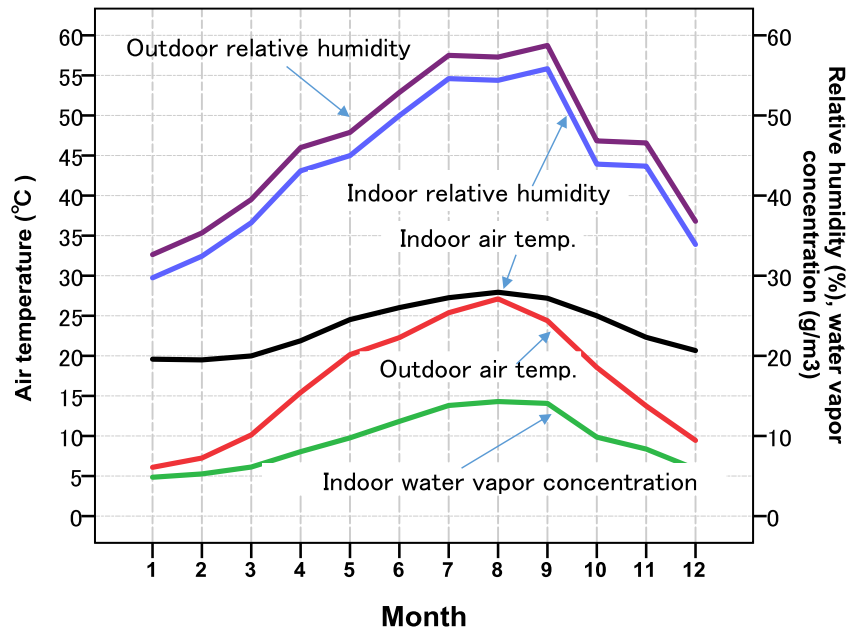


Figure 4.21 Monthly relative humidity and water vapor concentration with indoor air temperature.

The fact that the average indoor temperature stays rather constant during winter season from December to March is due to internal heat and solar heat gain together with the effect of thermal insulation and heat capacity of the materials used in the flats surveyed rather than the use of heating because similar indoor air temperature was also observed in even in FR mode. The fluctuation of indoor relative humidity is quite similar to the outdoor. Generally, 30-40% for winter and 60-70% for summer is assumed normal for 18-20°C in winter and almost 26°C air temperature for summer. The indoor relative humidity in this condominium seems with in this range.

The indoor air temperature and indoor relative humidity condition was observed to know their conditions and relation inside the studied buildings. Figure 4.22 shows that in CL mode the relative humidity is almost constant, the reason is the occupants have been using dehumidifier to control the humidity. In FR mode the linier line shows that the humidity increased with the increase of air temperature and decreased with the decrease of air temperature. But in HT mode, the relative humidity is high when the air temperature is low and relative humidity is low when the air temperature is high.

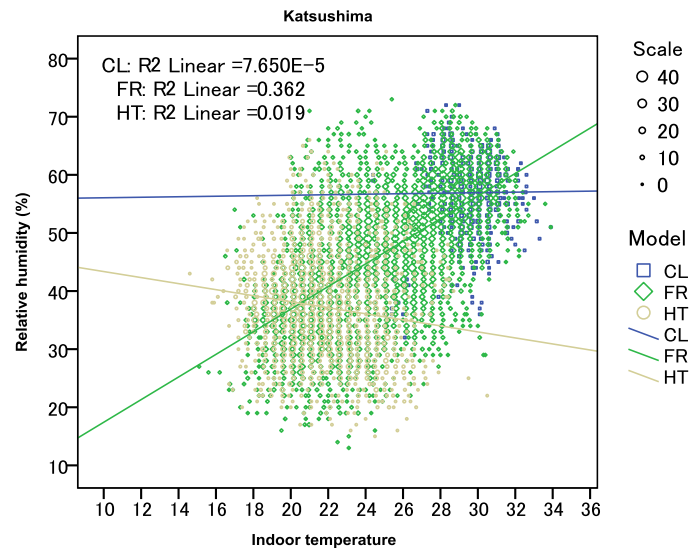


Figure 4.22 The relation of indoor air temperature and relative humidity

Figure 4.23 shows the relation of indoor air temperature and relative humidity in FR and CL mode during summer and FR mode and HT mode during winter.

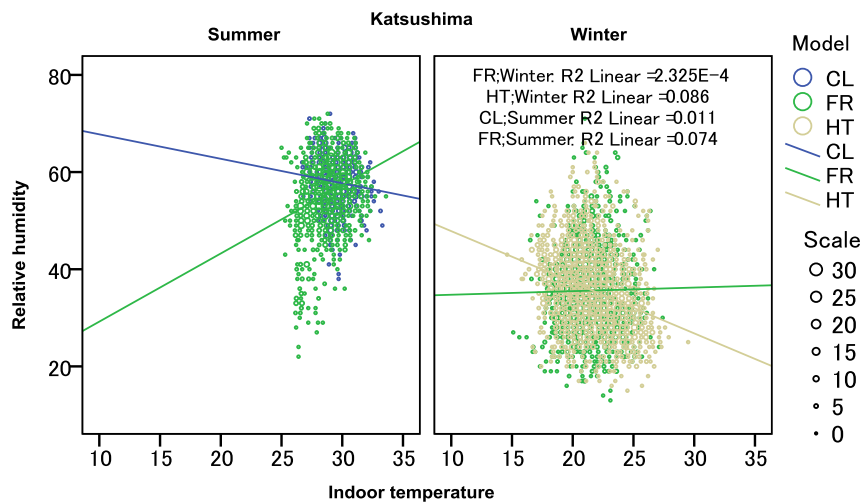


Figure 4.23 The relation of indoor air temperature and relative humidity in summer and winter

The linear line of FR mode in summer shows similar trend of relative humidity variation with the indoor air temperature. But in CL mode the trend is different. When the indoor air temperature is high, the indoor relative humidity is low. In winter, the relative humidity



is almost constant in FR mode but in HT mode, the relative humidity is low when the temperature is high and high when the indoor air temperature is low. When the air temperature was low the occupants used humidifier to increase the humidity for warm

#### 4.4 Water vapor concentration

Generally, it is difficult to understand the level of thermal comfort by observing the relative humidity only. So, we observed the amount of water vapor concentration per each family. As shown in Figure 4.24, the water vapor concentration is different by 4-5gm<sup>3</sup> between the flats during the time of voting in every month. The water vapor concentration gradually increased by 1-3 gm<sup>3</sup>/month moving to summer months and decreased with the same ratio moving to winter months. In summer months, the amount of water vapor concentration is high. The mean amount of water vapor concentration is different among the flats. Possibly, the number of occupants, window opening behaviors and the use of humidifier and dehumidifier might have the cause of this difference

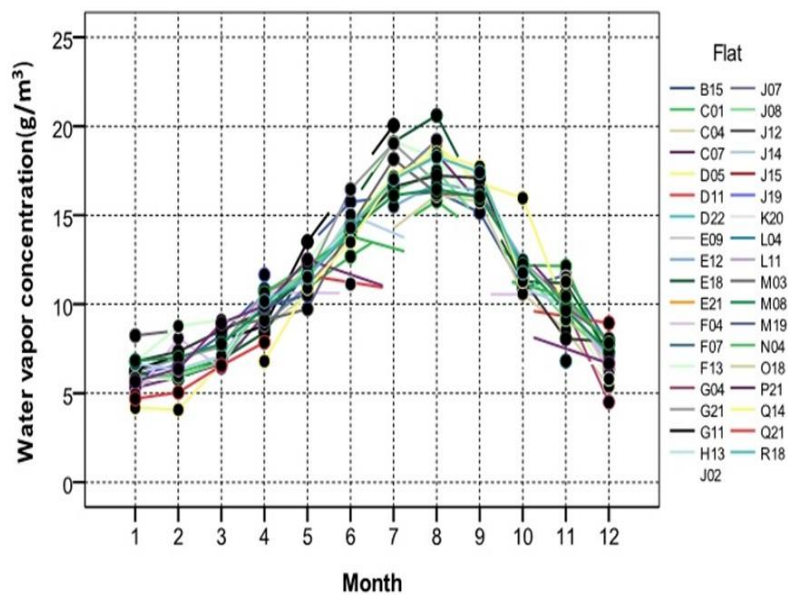


Figure 4.24 Monthly water vapor concentrations

Figure 4.25 shows that as the indoor air temperature increased, the amount of indoor water vapor concentration also increased. The outdoor water vapor concentration is also high when the indoor water vapor concentration is high.

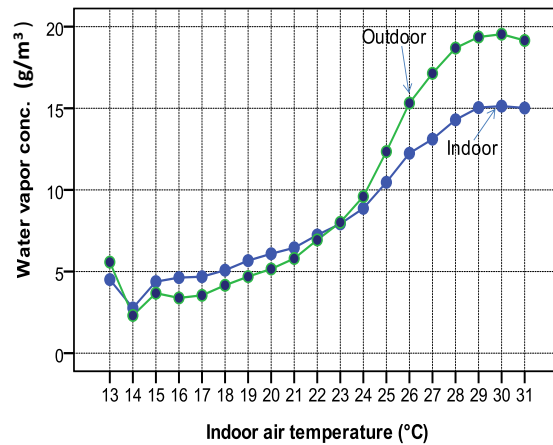


Figure 4.25 Indoor and outdoor water vapor concentration in terms of indoor air temperature

30°C indoor air temperature corresponds to 15g/m<sup>3</sup> of water vapor concentration indoor whereas the same indoor air temperature corresponds to 19g/m<sup>3</sup> water vapor concentration outdoor.

Figure 4.26 shows that as outdoor air temperature increased, the water vapor concentration also increased. 30°C outdoor air temperature corresponds to 14g/m<sup>3</sup> of water vapor concentration indoor whereas the same outdoor air temperature corresponds to 17g/m<sup>3</sup> water vapor concentration outdoor.

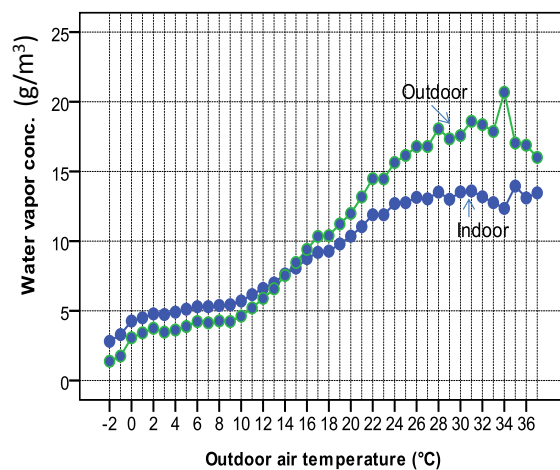


Figure 4.26 Indoor and outdoor water vapor concentration in terms of outdoor air temperature

## **4.5 Conclusions**

The monthly and seasonal differences in indoor air temperature and relative humidity are observed. The indoor air temperature in the studied condominium was not similar according to seasons, floors and flats. Even the building was equipped with HEMS systems, there is large range of temperature variation in indoor air temperature due to individual adaptive activities of the occupants similar to common detached houses and residential buildings. The amount of water vapor concentration is also different by flats and months. The amount of water vapor concentration increased by 2-2.5g/m<sup>3</sup> in every 10-15% increase in indoor relative humidity. The amount of water vapor concentration increased as the indoor air temperature increased. The occupants felt the indoor environment more humid when the amount of water vapor concentration increased. The indoor water vapor concentration has been influenced by outdoor water vapor concentration. When outdoor air temperature is high, the amount of water vapor concentration increased. The occupants felt neither humid nor dry between the ranges of 40-60% of relative humidity. The indoor air temperature in the studied condominium was observed dependent on outdoor air temperature in FR mode. The occupants mostly take FR mode rather than CL and HT modes. The mean indoor air temperature in winter was around 20°C which is similar even in FR mode. This is due to the thermal insulation level being rather better than conventional houses in Tokyo area. In CL mode, the mean indoor air temperature is 27.9°C which is similar to the recommended indoor air temperature equal to 28°C in summer in Japan.

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# Chapter 5: Adaptive Thermal Comfort of the Residents

## **5.1 Introduction**

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [1]. Indoor thermal comfort is associated with the trend of energy used in a building. The use of mechanical heating or cooling is the major behaviors of the occupants for indoor thermal comfort adjustments which are off course, the main reason for indoor energy use. Those living in coldest region may enjoy sufficiently warm built environment, while on the other hand, those in temperate regions may not perceive warm enough due to a lack of proper heating systems [2]. On the other hand, over heating or over cooling may result excessive use of energy. There are different guidelines made for indoor heating and cooling and for indoor comfort temperature. But those existing guidelines in dwellings are inappropriate and could be more flexible [3-6]. Comfort in free running (FR mode) in both domestic and non-domestic building relates with outdoor conditions so the temperature range will be high [7]. It is believed that buildings with mechanical heating and cooling have narrower temperature than without it because it is assumed that the indoor environment will be well controlled [8]. In the field studies, people flexibly adapted their behaviors to ensure thermal comfort [9]. In order to achieve thermal comfort, humans have developed some adaptive approaches to adapt their natural environment such as opening windows, changing their clothes, activity level or take hot or cold drinks. The occupants by behavioral adaptation can achieve thermal comfort at a relatively higher indoor air temperature in summer and a relatively lower indoor air temperature in winter compared with that in PMV model [5]. Even in mechanical heating and cooling buildings, there may be wide range of indoor conditions due to differences in indoor adaptive behaviors.

## **5.2 Thermal sensation votes (TSV)**

We took the thermal sensation votes of the occupants to understand the occupants' thermal sensation level for hot or cold. We have received fewer votes in CL and HT in comparison to FR mode as shown in Figure 5.1. It means that the occupants were accustomed to use passive means to adjust indoor environment and they have used

heating and cooling devices only during severe hot and cold months. The largest number of votes has been received for 4 (neutral) in all modes. In FR mode, the mean value of TSV (thermal sensation vote) is 4 representing thermal comfort levels high. The occupants have used FR mode when they were not in CL and HT mode in the whole year so there are also some votes slightly shifting to both hot side and cold side in FR mode. There are some votes slightly shifting to hot side in CL mode and slightly to cold side in HT mode.

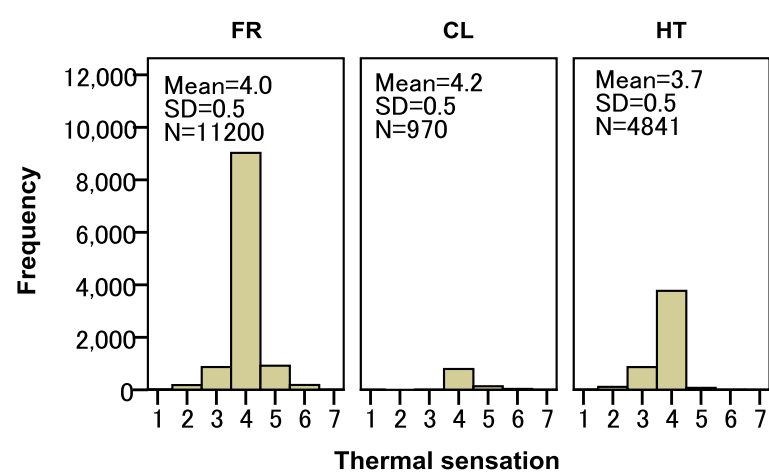


Figure 5.1 Thermal sensation votes in different modes

We also observed the thermal sensation responses of the occupants in FR mode for summer and winter. If we observe TSV of FR mode in summer and winter as shown in

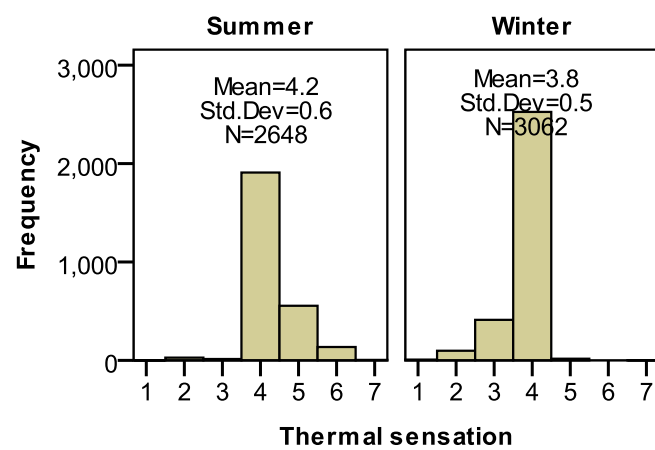


Figure 5.2 Thermal sensation votes in summer and winter for FR mode

In Figure 5.2, the highest number of votes is neutral in both seasons. There are few votes shifting towards cold side in winter and hot side in summer.

We further analyzed the thermal responses of the occupants according to the age groups. Figure 5.3 shows the number of votes received from the occupants of different age groups. The highest number of votes were received from the age groups of 30-34, 35-39, 40-44 and 55-59. Form the analysis it is more clear that which age groups people were higher in number in the studied condominium.

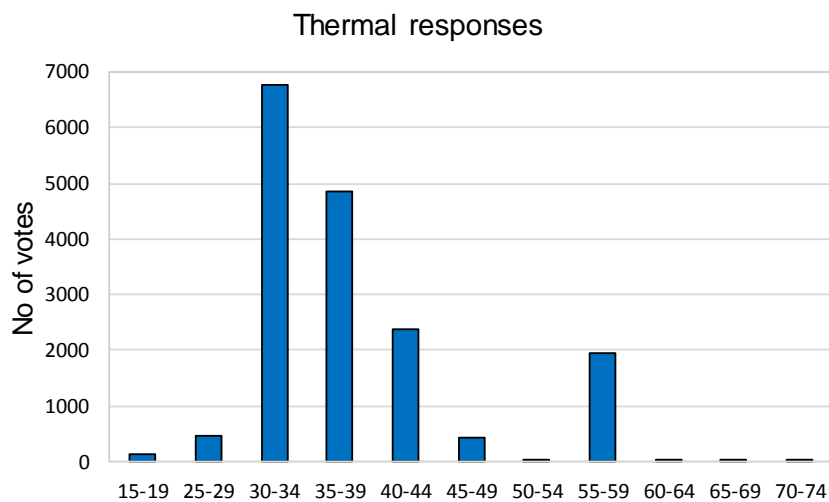


Figure 5.3 The number of votes for thermal responses

Figure 5.4 shows the level of thermal sensation according to different age groups in different modes. The mean thermal sensation of different age groups is quite close to 4 that is neutral in all the modes. In FR mode, most of the age groups mean is quite close to neutral. In CL mode, age group from 55-59 have the mean 5 that is slightly hot. The mean thermal sensation votes of the age groups from 15-19 is slightly shifting towards cold side and the mean thermal sensation votes of the age groups from 55-59 is slighting shifting to hot side. The possible reason might be due to body types preferring warm or cold. The age factor might be the another reason.

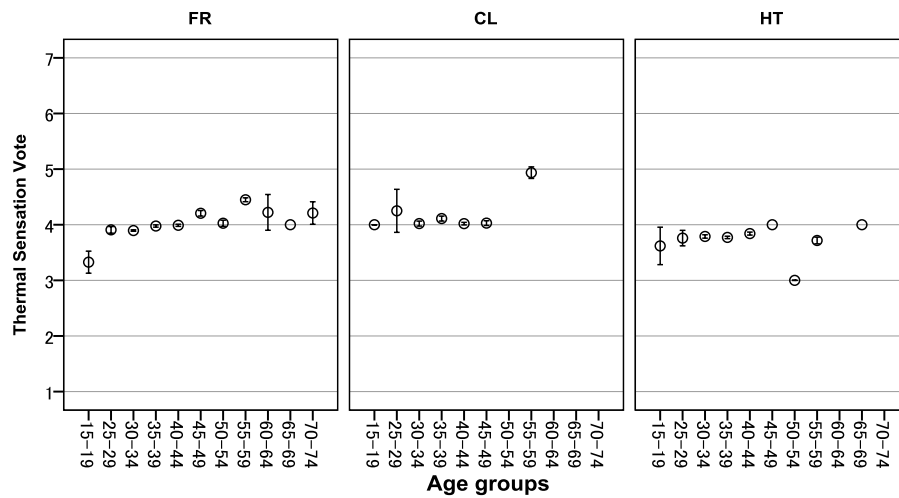


Figure 5.4 Thermal sensation of different age groups in different modes

### 5.3 Thermal preference

Thermal preference is analyzed to understand whether the occupants are comfortable with the environment or prefer some warmer or cooler environment. As shown in Figure 5.5. The highest numbers of votes are for 3 that is no change in all the modes. It indicates that the most of the occupants do not prefer to make a change to warmer or cooler environment. There are some votes preferring a bit cooler in CL mode and a bit warmer in HT mode.

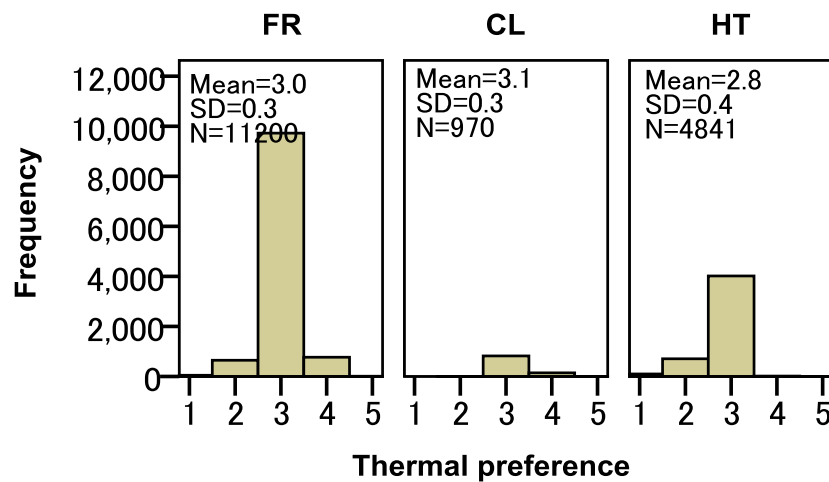


Figure 5.5 Thermal preference of the occupants in different modes



We also tried to study the thermal preference level of FR mode in summer and in winter separately. If we observe the mean thermal preference of error bar diagram as shown in Figure 5.6, the mean is close to 3 which is no change. The mean of summer is slightly higher than 3 due to some votes preferring a bit cooler. In the same way the mean of winter is slightly less than 3 due to some votes preferring a bit warmer.

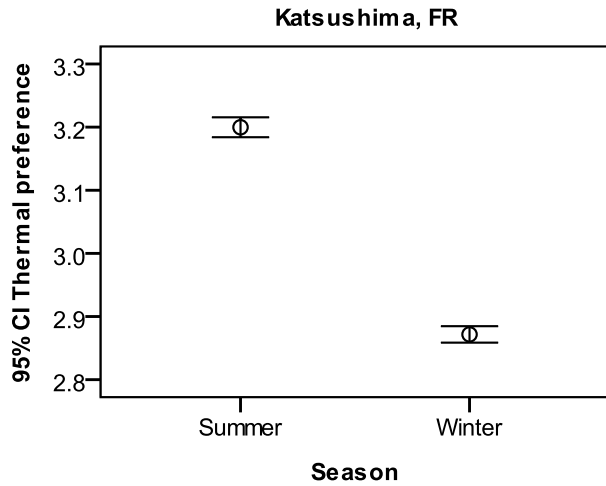


Figure 5.6 Thermal preference of the occupants in summer and winter in FR mode.

We further analyzed the thermal preference of the occupants according to different age groups in three different modes. Figure 5.7 shows the level of thermal preference according to different age groups.

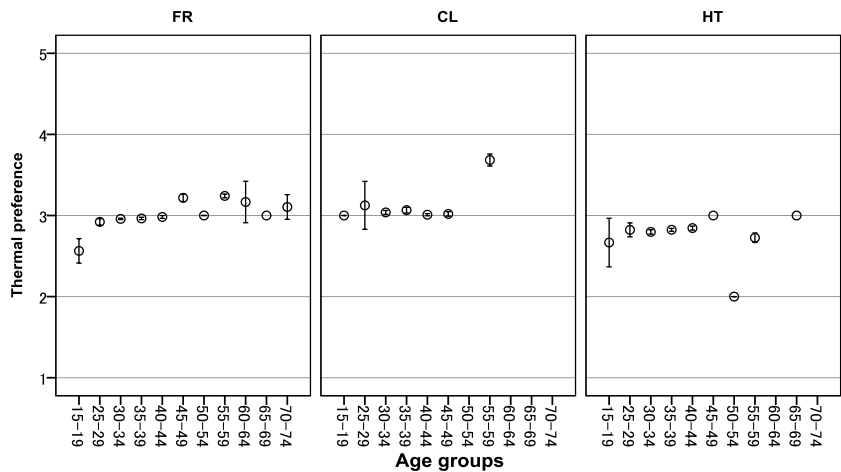


Figure 5.7 Thermal preference of different age groups in different modes

The mean thermal preference of different age groups is quite close to 3 that is no change in all the modes. The mean thermal preference votes of the age groups from 15-19 is slightly shifting towards preferring warmer and the mean thermal sensation votes of the age groups from 55-59 is slightly shifting to preferring cooler in FR mode.

#### 5.4 Thermal Satisfaction

Thermal satisfaction level of the occupants was observed to understand to what extent the occupants were satisfied with the indoor thermal environment.

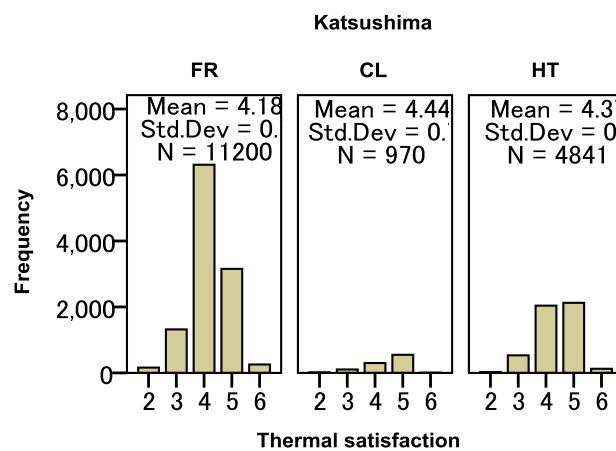


Figure 5.8 thermal satisfaction of the occupants in different mode

The thermal satisfaction condition of the occupants residing in the study area was noticeable. As we see in Figure 5.8, the highest number of occupants voted for 4 that is slightly satisfied and 5 that is satisfied as indicated in six points thermal satisfaction scale. There are few votes for very satisfied as well but there are no votes for very unsatisfied.

We further observed the satisfaction level of the occupants in FR mode during summer and winter. As shown in Figure 5.9.

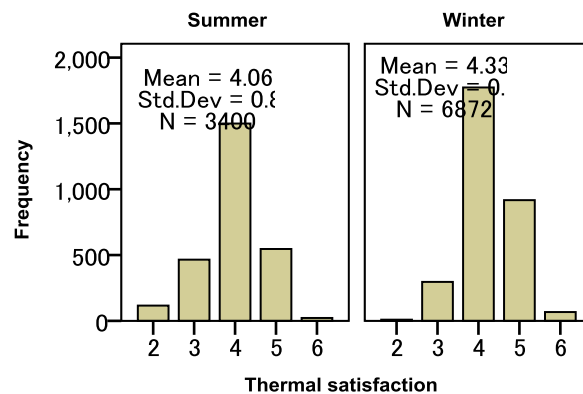


Figure 5.9 Thermal satisfaction of the occupants in summer and winter in FR mode

The highest number of votes were received for 4 and 5 which are slightly satisfied and satisfied respectively. Some fewer votes distributed to slightly unsatisfied and unsatisfied side as well especially in summer. The overall result of thermal satisfaction shows that the occupants are satisfied with the indoor thermal environment.

We further analyzed the thermal satisfaction of the occupants according to different age groups. Figure 5.10 shows the level of thermal satisfaction according to different age groups.

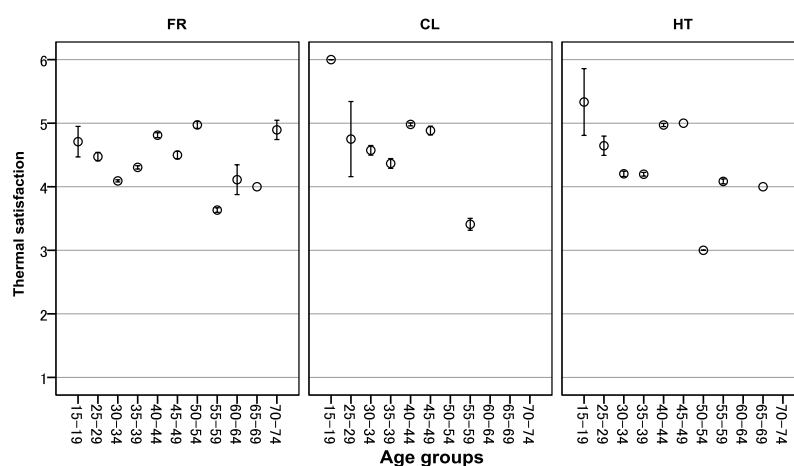


Figure 5.10 Thermal satisfaction of different age groups in different modes

The mean thermal satisfaction of different age groups is between 4 and 5 are that slightly satisfied and satisfied respectively. The mean thermal satisfaction votes of the age groups from 15-19 seems more satisfied than other groups as the mean is quite close to satisfied. The age group from 55-59 is slightly shifting to 3 that is slightly unsatisfied. The possible reason might be due to body types preferring warm or cold. The age factor might be the another reason.

### 5.5 Overall comfort

The thermal response analysis so far has confirmed that the thermal comfort level of the occupants residing in the studied building is quite high. We further analyzed overall comfort in three modes. Figure 5.11 shows the result that the highest votes were for 4 and 5 that are slightly comfortable and 5 comfortable respectively. The result showed that the mean overall comfort is close to in CL and HT modes than in FR mode.

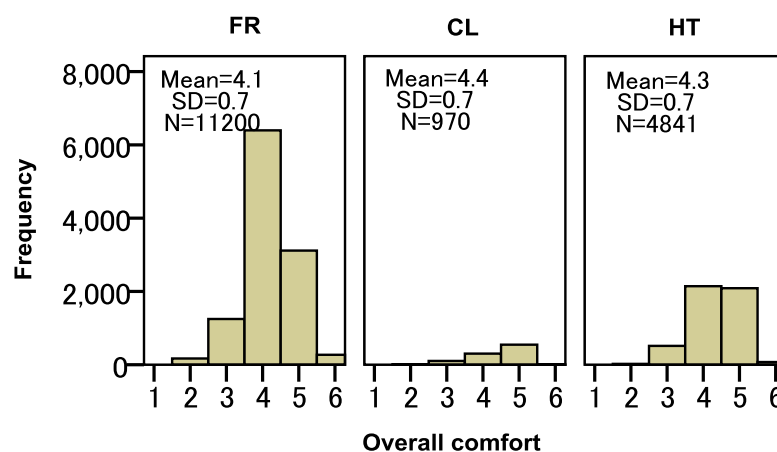


Figure 5.11 thermal satisfaction of the occupants in different modes

If we observe the overall comfort of FR mode in summer and winter as shown in Figure 5.12, the highest number of votes is 4 “slightly comfortable” and 5 “comfortable”. There are also some votes for very comfortable. Some votes mentioned slightly uncomfortable and uncomfortable but there are not any votes for very uncomfortable.

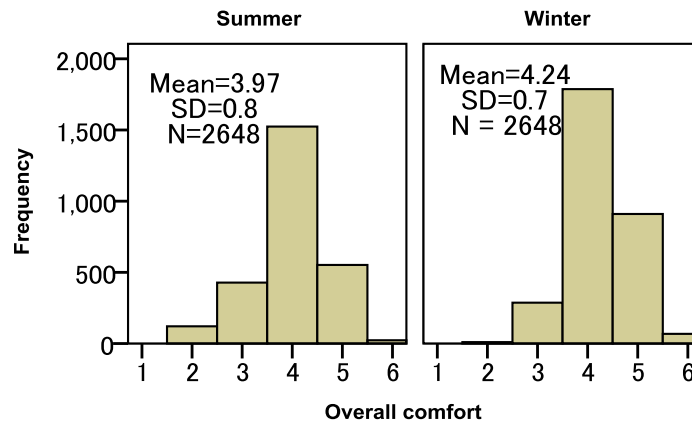


Figure 5.12 Overall comfort of the occupants in summer and winter in FR mode

We further analyzed the overall comfort of the occupants according to different age groups in different modes. Figure 5.13 shows the level of Overall comfort according to different age groups. The mean Overall comfort of different age groups is between 4 and 5 are that slightly comfortable and comfortable respectively. The mean Overall comfort votes of the age groups from 55-59 is slightly shifting to 3 that is slightly uncomfortable. The possible reason might be the age factor.

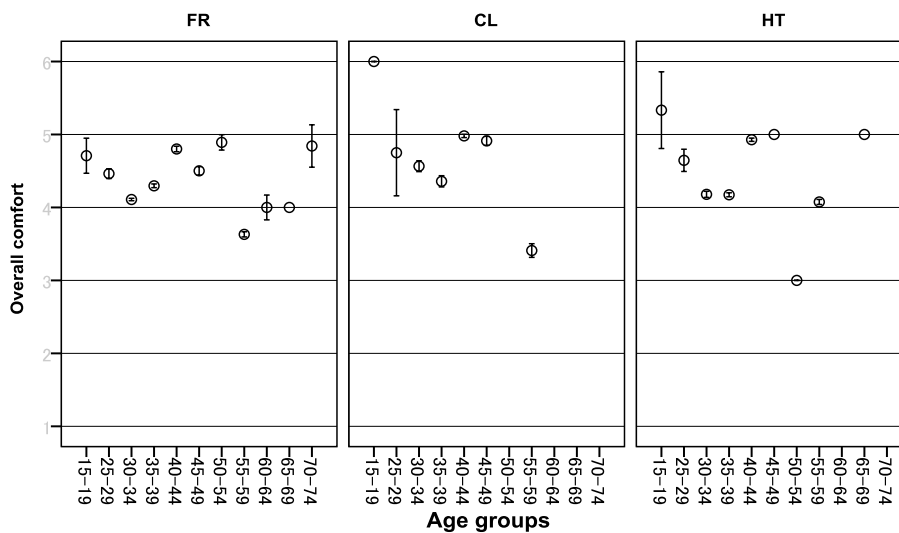


Figure 5.13 Overall comfort in summer and winter in FR mode

We also observed the overall comfort votes of the occupants in different seasons for FR mode. The similar trend is observed in FR mode in all four seasons as shown in Figure 5.14. There are very few votes shifting to slightly uncomfortable and uncomfortable in all the seasons. Most of the occupants seem comfortable with the given indoor thermal environmental condition.

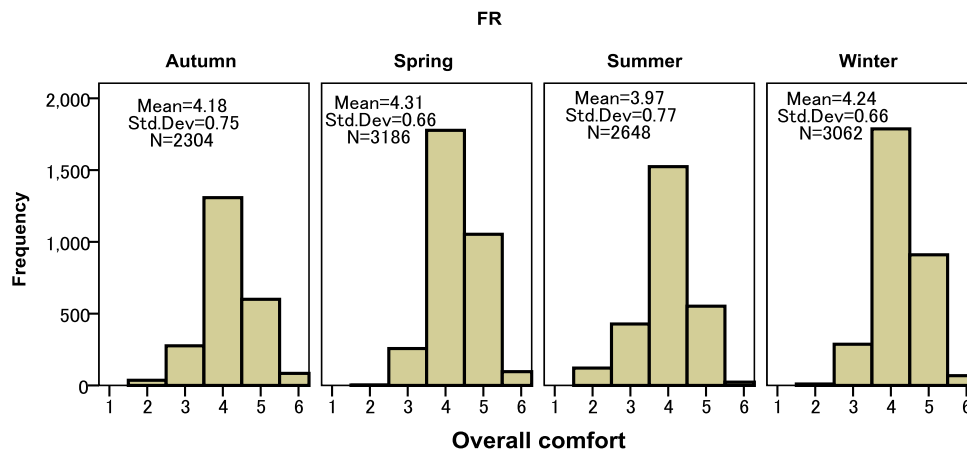


Figure 5.14 Seasonal overall comfort

Table 5.1 shows the average indoor air temperature corresponding to each of the seven point scales in respective modes.

Table 5.1 Seasonal indoor air temperature with standard deviation

TSV	$T_i$ in FR (°C)								$T_i$ in CL (°C)		$T_i$ in HT (°C)	
	Summer		Winter		Autumn		Spring		Mean	SD	Mean	SD
	Mean	SD	Mean	SD	Mean	SD	Mean	SD				
1	-	-	19.6	3.9	-	-	-	-	-	-	18.6	4.2
2	-	-	22.6	2.2	26.4	2.0	24.6	2.7	-	-	21.9	2.7
3	27.3	1.5	21.7	2.1	24.2	2.3	24.5	2.6	24.4	0.0	21.6	2.3
4	28.6	1.3	21.1	1.8	25.7	2.8	24.9	2.3	29.7	1.2	21.6	2.2
5	29.1	1.3	22.8	1.8	28.2	2.5	25.9	1.2	30.2	1.3	22.0	2.7
6	29.6	0.1	-	-	29.3	1.7	27.1	0.5	30.2	1.3	-	-
7	29.8	0.9	-	-	-	-	-	-				

$T_i$ : Indoor air temperature, FR: Free running, CL: Cooling, HT: Heating

In summer, 28.6°C corresponds to TSV 'neutral' and 21°C in winter. This implies that there is 7.6°C difference in the neutral temperature between summer and winter. In autumn, it is 25.7°C and in spring it is 24.9°C. This difference is marginal. In CL mode, it is 29.7°C and, in HT mode, it is 21.6°C and their difference is 8.1°C. That is, the same TSV corresponds to different temperature according to the types of mode. This is probably due to the level of clothing insulation differences. Previous study has proved that there is the relation between the clothing insulation and thermal sensitivity [28].

In order to further verify the overall characteristic of TSV in relation to indoor air temperature, we sorted the TSV votes into a group of 'discomfort' (very cold, cold, hot and very hot) and the other group of 'comfort' (slightly cold, neutral and slightly hot) and then the proportion of comfort among all TSV votes for the bins of 0.5°C ranges of indoor air temperatures calculated. Figure 5.15 shows the result of calculation. The following quadratic regression equation is obtained between proportion of comfort 'Pcomfort' and indoor air temperature.

$$P_{\text{comfort}} = -0.0018T_i^2 + 0.0820T_i + 0.054$$

$$(n = 6728, R^2 = 0.027, S.E._1 < 0.001, S.E._2 = 0.01, p_1 \text{ and } p_2 < 0.001) \quad 5.1$$

where, S.E.<sub>1</sub> and S.E.<sub>2</sub> are standard error of the regression coefficient of  $T_i^2$  and  $T_i$  respectively and  $p_1$  and  $p_2$  is the level of significance for the regression coefficient of  $T_i^2$  and  $T_i$ .

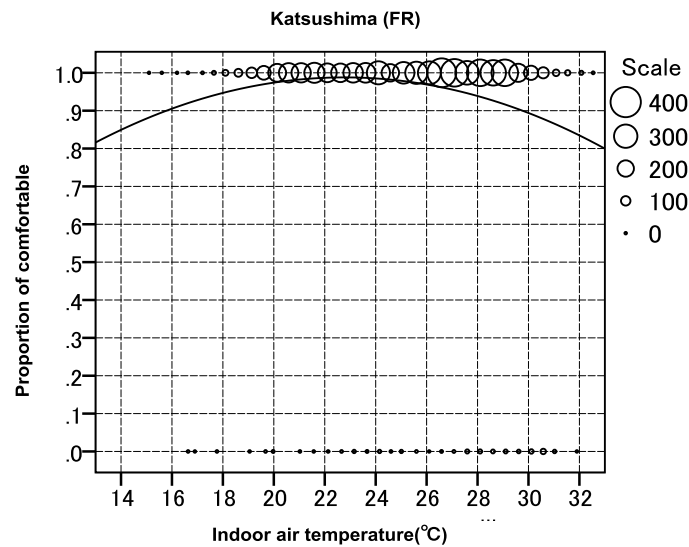


Figure 5.15 Relation between comfort and air temperature

The temperature that results in the maximum value of Pcomfort is equal to 22.8°C. It does not mean that the occupants must maintain the temperature equal to 22.8°C. the highest level of comfort is observed at this point. The occupants are more comfortable between the range of 22 to 28°C range. The proportion of 'comfort gradually decreases below or above the optimum temperature. The value of Pcomfort at 90% is given at 16°C and at 30°C. The neutral temperature described above as shown in Table 5.1, from 21.1 to 29.7°C are confirmed to be within this range.

### 5.6 Thermal acceptance

Thermal acceptance of the occupants has been analyzed to understand whether the occupants have accepted the indoor environment at the moment of voting or not. Figure 5.16 show that the highest percentage of the people has accepted the indoor environment inn summer. They have accepted the thermal environment because they were comfortable with that indoor thermal environment.

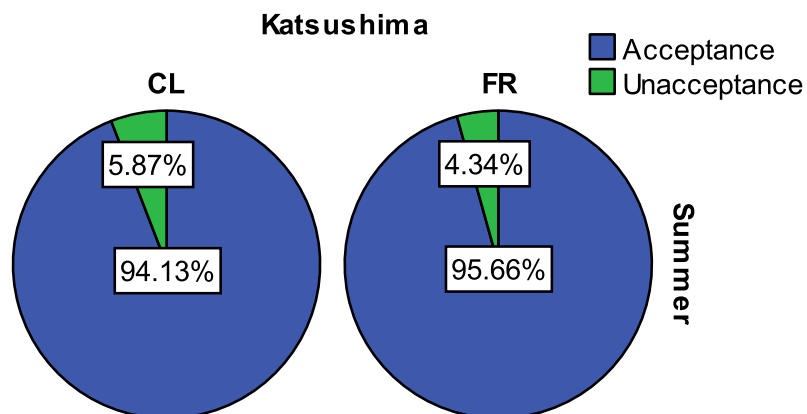


Figure 5.16 Thermal acceptance in Summer

As shown in Figure 5.17, the thermal acceptance in FR mode is slightly higher than CL mode but in winter, the thermal acceptance in FR mode is slightly lower than HT mode.



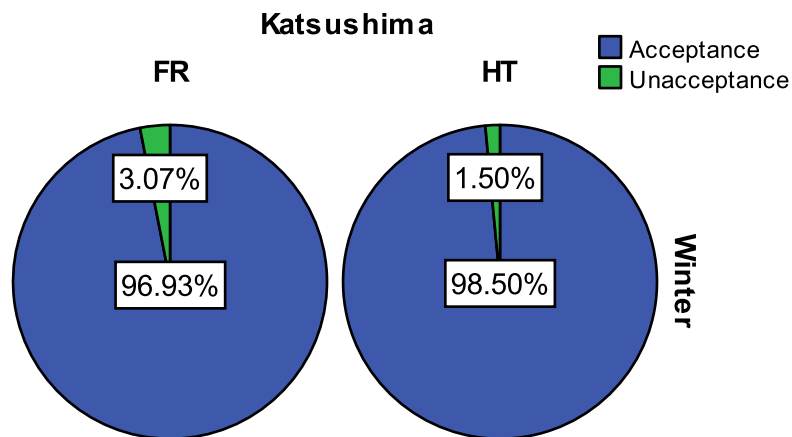


Figure 5.17 Thermal acceptance in winter

### 5.7 Relationship between thermal sensation and thermal preference

The relationship between thermal sensation and thermal preference of the occupants was analyzed to understand how the occupants prefer in terms of thermal sensation votes. We also wanted to confirm that the scale that has been used match with each other or not

Thermal preference scale with five points was converted into categories 'preferring warmer' (both of 'a bit warmer' and 'much warmer'), 'no change' and 'preferring cooler' (both of 'a bit cooler' and 'much cooler') and then the number of votes corresponding to these three categories are expressed in percentage. The result was then compared with thermal sensation with seven point scales. Figure 5.18 shows how the cumulative percentage values of the occupants 'preferring warmer' or 'preferring cooler' corresponding to the seven point's scale of TSV. The occupants with TSV towards cold side want to make it warmer and those with TSV towards hot side want to make it cooler. 82% of the occupants voting TSV '3 slightly cold' prefer warmer and also 75% of the occupants voting '5 slightly hot' prefer cooler. All of the occupants voting either TSV '2 cold' or '1 very cold' prefer warmer while on the other hand those voting TSV '6 hot' or TSV '7 very hot' prefer cooler. Almost 100% of the occupants prefer 'no change' when their TSV is a '4 neutral', 30% of the occupants prefer 'no change' when TSV is '3 slightly cold', and almost 40% prefer 'no change' when TSV is '5 slightly hot'. These tendencies must be well related to having the adaptive opportunities for thermal comfort. The number of data corresponding to TSV of '1 very cold' and '7 very hot' is very small

so that the percentage value corresponding to those categories are not reliable.

We may say that, for TSV being 3 or 5, which is 'slightly cold' or 'slightly hot', approximately 80% of occupants perceived 'preferring warmer' or 'preferring cooler' respectively, but the rest, 20%, still regards no change is necessary. According to similar study on Nepalese people carried out by Rijal et al. [11], the proportion of people 'preferring cooler' and 'preferring warmer' is higher than that in this study. It could be because Nepalese people expose to hot and cold environment in everyday life, more than Japanese people do in summer and winter. This analysis proved that the votes of TSV are well related to the proportions of the 'preferring cooler' and 'preferring warmer'. The occupants with TSV towards cold prefer warmer and the TSV towards hot prefer cooler. These scales matched well with each other. We can say that the votes of preference and thermal sensation given are consistent with each other.

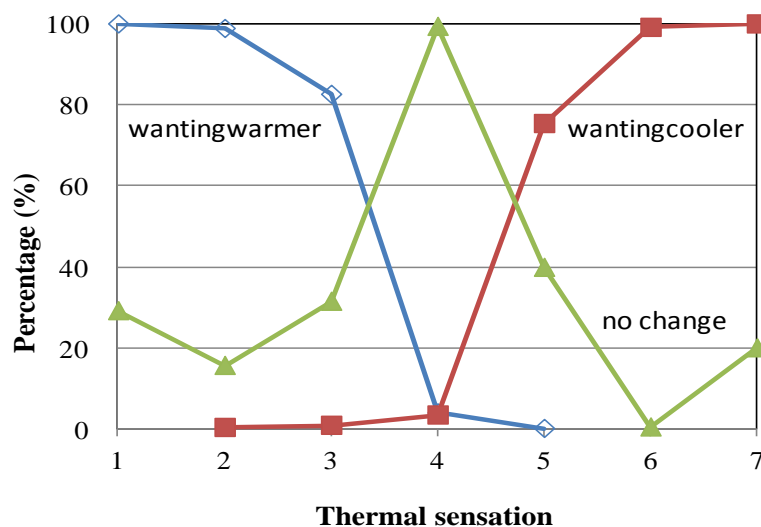


Figure 5.18 Relation of indoor air temperature and comfort

### 5.8 Humidity feeling and skin moisture feeling

We analyzed the occupants' perception of humidity in relation to the indoor relative humidity using the scale as shown in Table 5.2. We analyzed the occupants' perception of relative humidity and skin moisture in terms of the relative humidity and the amount of the water vapor present inside the indoor air. The occupants' humidity feeling is different according to the modes as shown in Figure 5.19. They felt more humid when the

relative humidity is high and dry when the humidity is low. The humidity feeling for neither humid nor dry is between the ranges of 40- 60%. The occupant's humidity perception and skin moisture perception is different according to modes.

Table 5.2 Air temperature preference and humidity feeling scale

Scale	Preference	Humidity feeling	Skin moisture feeling
1	Much warmer	Very dry	None
2	A bit warmer	Dry	Slightly
3	No change	Slightly dry	Moderately
4	A bit cooler	Neither dry nor humid	Profuse
5	Much cooler	Slightly humid	
6		Humid	
7		Very humid	

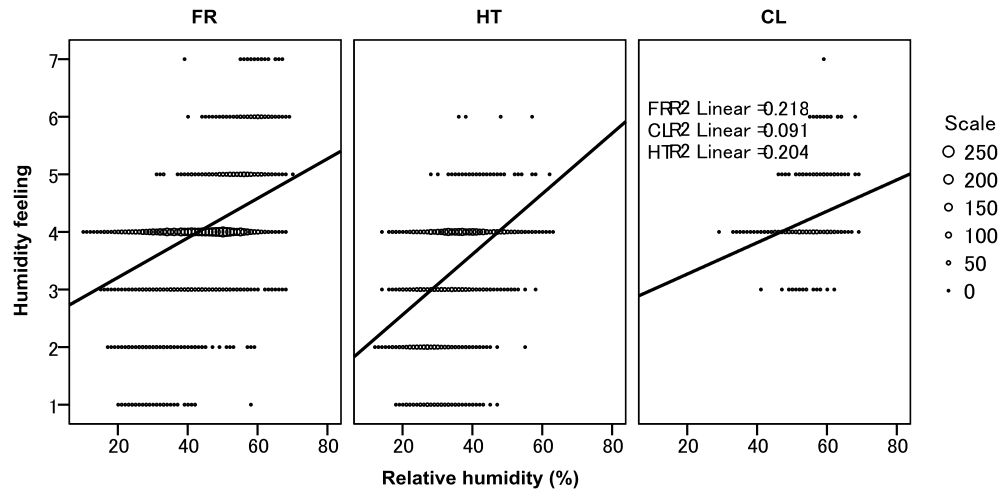


Figure 5.19 Relation between indoor relative humidity and humidity feeling

Figure 5.21 shows that high water vapor concentration led the occupants feel more humid and less water vapor concentration led the occupants feel dryness.

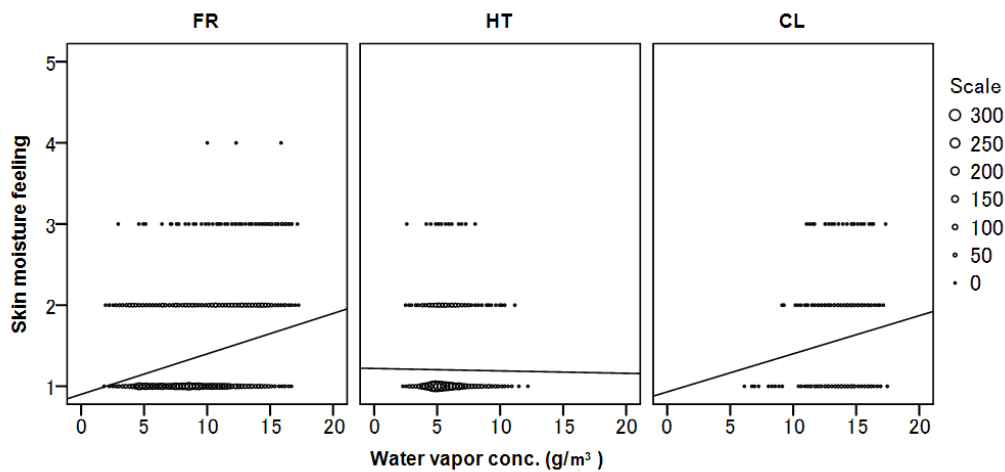


Figure 5.20 Relation between water vapor concentration skin moisture feeling

The amount of water vapor concentration for neutral (4) is different according to modes. It might be due to seasonal differences. Figure 5.21 shows that the occupants felt slightly more skin moisture in CL mode and FR than HT mode.

## 5.9 Conclusions

The level of indoor thermal comfort is high. The thermal sensation votes were mostly neutral in all modes. The large numbers of votes in terms of preference was 'no change' in both summer and winter seasons. Very few were found to prefer change. The TSV were observed related to the occupants' preference of 'preferring cooler' and 'preferring warmer'. The maximum proportion of comfort was equal to 22.8°C of indoor air temperature. The proportion of 'comfort' at more than 90% was 27.5°C for the higher temperature and 18°C for lower.

The indoor relative humidity increased or decreased the humidity feeling of the occupants changed. They felt more humid when the relative humidity is high and dry when the humidity is low. But the humidity feeling for neither humid nor dry is between the ranges of 40-60 %. The occupants felt the indoor environment more humid when the amount of water vapor concentration increased.

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# Chapter 6: Behavioral Adjustments

## 6.1 Introduction

Occupants residing in any types of buildings adapt passive and active methods to indoor thermal environment given by and maintain their thermal comfort inside the buildings. Commonly, passive methods are window opening and clothing and active methods are mechanical heating and cooling.

## 6.2 Window opening

The proper opening and closing of windows can help to regulate the thermal environment so that it is important as one of the adaptive behaviors [1]. Thermal discomfort is caused by the indoor globe temperature and opening a window produces a mixing of indoor and outdoor air (when outdoor air temperature is low) and help to drop the indoor air temperature [2]. The condition of window opening was observed to analyze how the occupants were adjusting thermal comfort in terms of natural way of thermal adjustment.

The proper opening and closing of windows can help to regulate the air flow smoothly that may help to improve the thermal environment so that it is one of the important adaptive behaviors [3].

Figure 6.1 showed that the occupants were equally using window open in different months but the proportion is high in May, June, July, August and September.

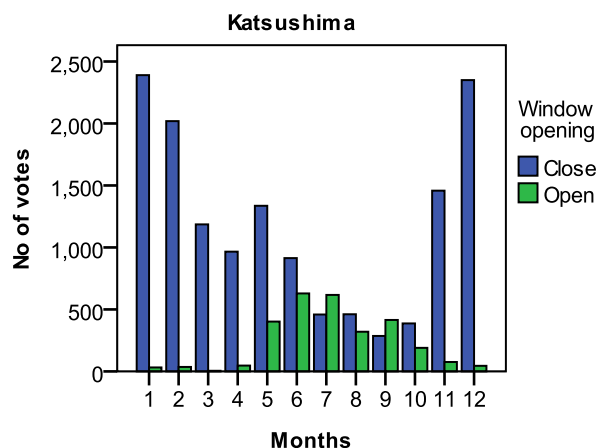


Figure 6.1 Monthly window open or close

The proportion of window opening decreased in November and December. The reason must be the occupants started using heating.

Figure 6.2 shows that large proportion of the occupants adapted window opening in summer months June, July and August. The highest 0.8 proportion of the occupants opened window in July. In August, it is slightly decreased. Maybe, the occupants closed the window and started using cooling.

We further analyzed the window opening behaviors by dividing the total data according to voting time indoor air temperature into 10 (deciles) groups of around 1000 number of data in each group and the mean temperature of that particular group was taken

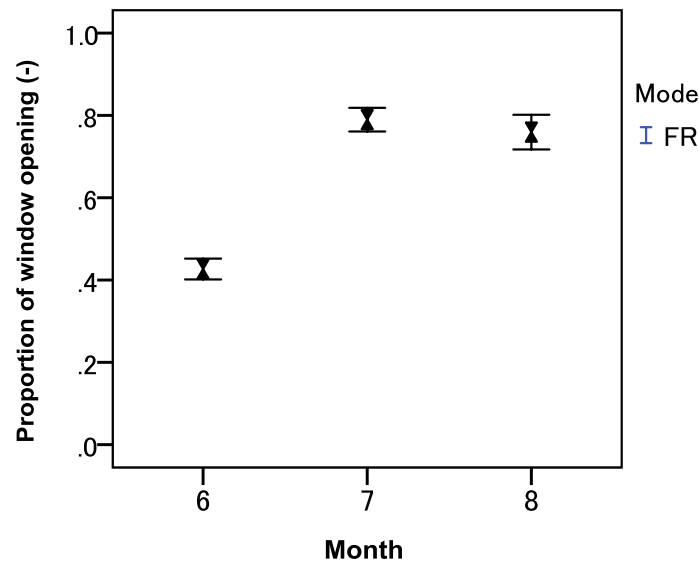


Figure 6.2 Window opening in Summer months in FR mode

As can be seen in Figure 6.3, the proportion of the window opening increased as the indoor air temperature increased. When the mean indoor air temperature is between 28-30°C almost 40 to 50% kept the window open. Imagawa and Rijal [3] have found that 0.55 proportion of window kept opened when the outdoor air temperature is 28°C, in this study 0.45 proportion of window kept opened when the outdoor air temperature is 28°C. This proves that the occupants in this condominium with HEMS, tend to prefer window opening for thermal comfort.

As we have mentioned earlier in section 4.2.1 that we listed those flats with both measurement data and questionnaire data and divided them into four groups according to the condition of high and low indoor air temperature in summer and winter.

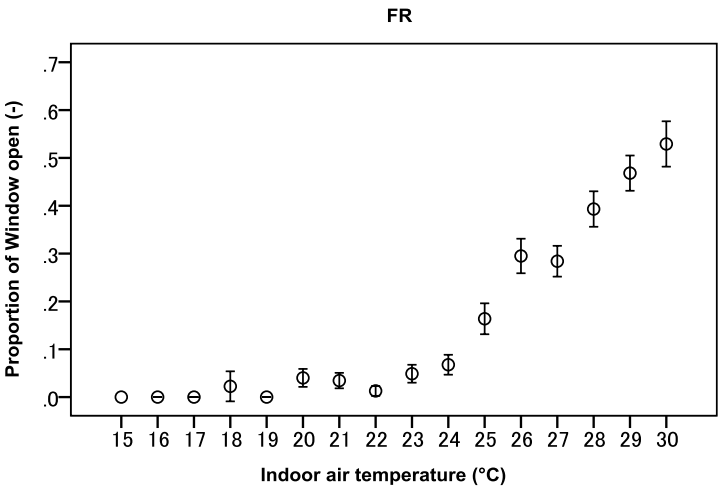


Figure 6.3 Relation between indoor air temperature and window open

We observed the window opening behaviors of the two groups with higher and lower indoor air temperature in summer. Figure 6.4 shows the proportion of the window open of higher and lower temperature groups.

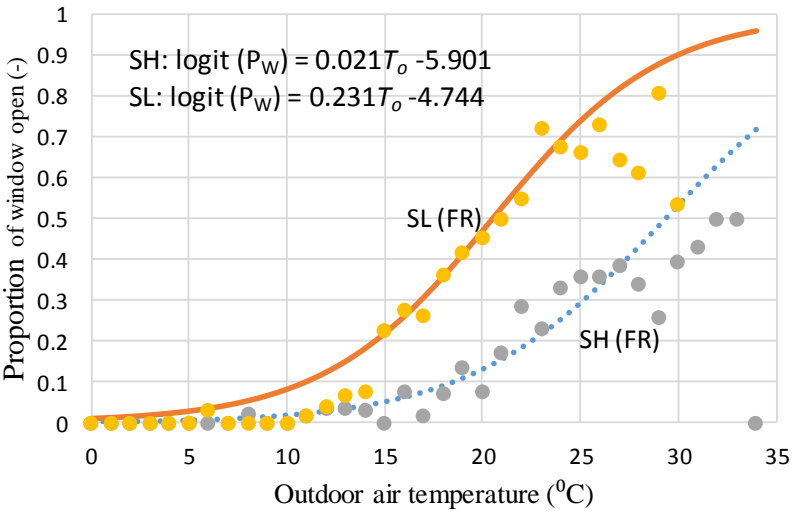


Figure 6.4 The proportion of the window open of higher and lower temperature groups.



The window opening behavior gradually increase as the outdoor air temperature increases but the proportion of window open of SH is lower than SL. At 25°C, the proportion of the window open turned to be 0.70% for SL but it is just 0.30% for SH. The natural ventilation took place well by window opening behavior that helped the occupants remain comfortable with rather high indoor air temperature

### 6.3 Internal door open

Indoor thermal comfort and indoor air quality is mainly affected by ventilation rate. As the window and internal door open, the ventilation takes place and help to improve the indoor thermal environment. A study in Hong Kong [4] showed that most of the people felt stuffy because of poor indoor air quality. Although we have not measured the air velocity during the survey but we have taken the respondents' votes for window and internal door open.

The measurement of indoor thermal environment was conducted in living room suggests that the internal door open or close may play an important role to determine the indoor air quality and indoor air temperature. Figure 6.5 shows that a large proportion of the occupants kept their internal door open but the proportion is high in summer months June, July and August which definitely helped to improve the indoor thermal environment.

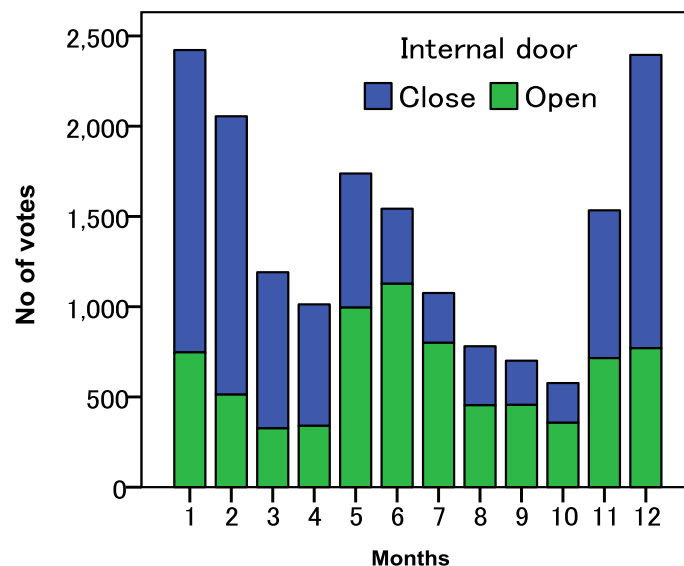


Figure 6.5 The proportion of internal door open in different months

We observed the window opening behaviors of two separate groups with higher and lower temperature. Figure 6.6 shows the proportion of internal door open for SL is higher than SH in summer. Possibly, for SL group the ventilation took place well resulting lower indoor air temperature in FR mode.

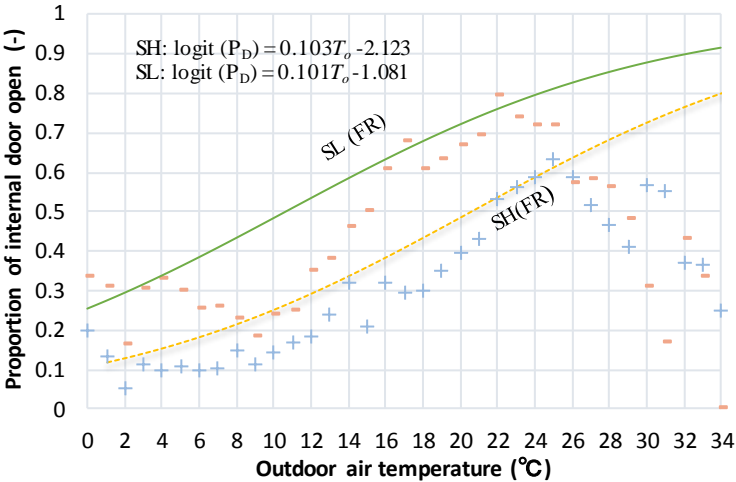


Figure 6.6 Proportion of internal door open for Lower and higher temperature groups

Figure 6.7 shows that the comfort temperature can increase by 3°C if the air velocity has been increased up to 1m/s.

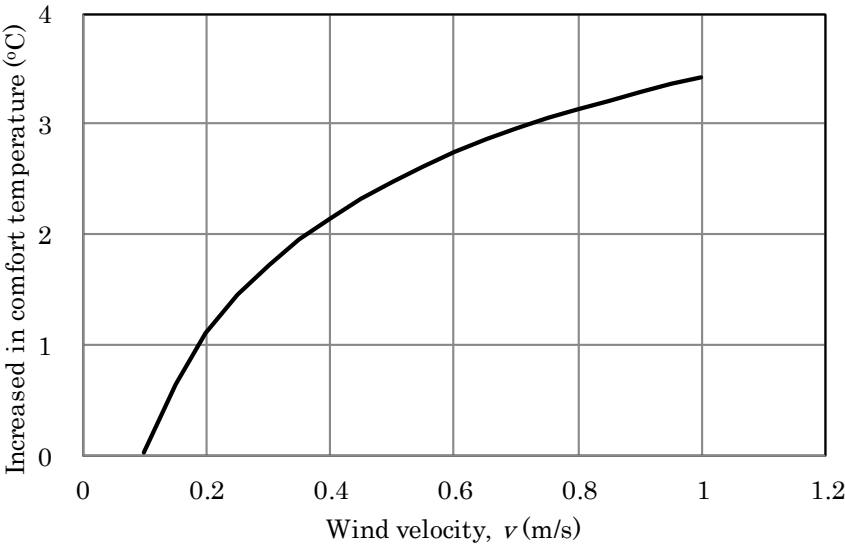


Figure 6.7 Relation of air velocity and comfort temperature [4]

Though, we do not have the air velocity measurement but we analyzed the window opening and door opening behaviors. When the window and door are open the air ventilation took place well that might have helped the occupants feel comfortable even with high indoor air temperature.

#### 6.4 Clothing insulation

Clothing is one of the active behaviors for thermal comfort adjustments. Generally, the occupants are free to adjust their clothing in their residents with and any constraints. In this section, the mean clothing insulation in different months was observed to understand the clothing behaviors of the occupants. As we see in Figure 6.8, the clothing insulation decreased in summer and increased in winter. The highest clo value is observed in January equal to 0.95 clo. The lowest clothing insulation is observed in September which is equal to 0.40 clo.

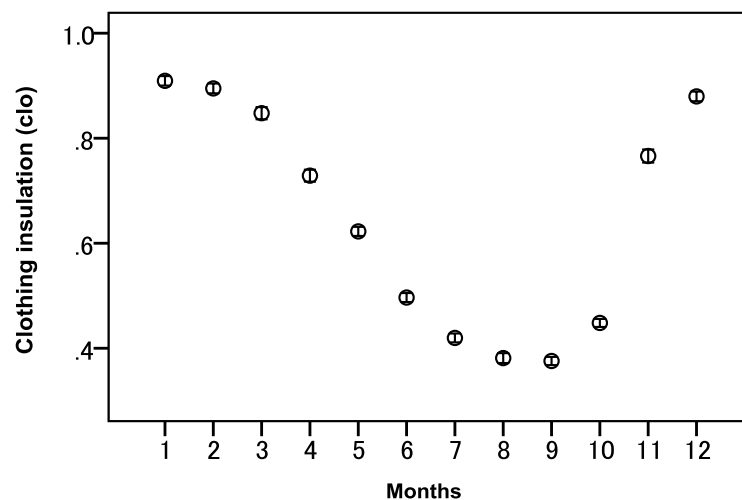


Figure 6.8 Monthly clothing insulation

The mean clothing insulation with 95% confidence interval (Mean  $\pm$ 2 S.E.) in different modes was obtained from the surveyed data. Figure 6.9 a shows the trend of clothing during FR, HT and CL mode.

The clo value is lower in CL mode and higher in HT mode. The mean clothing insulation is 0.71 clo. The mean clo is 0.65 (n=11176), 0.40 (n=965) and 0.94 (n=4839) in FR, CL and HT mode respectively. Clothing influences heat exchange between human body and the thermal environment, contributing to thermoregulation by creating a moderate micro-climate within the fabric layer [5].

Previous studies [5-10] have proved that clothing is equally adjusted to maintain thermal comfort in different research area. The monthly mean clothing insulation has the similar trend of clothing insulation compare to the study made by Watanabe et al. in Gifu area of Japan [7].

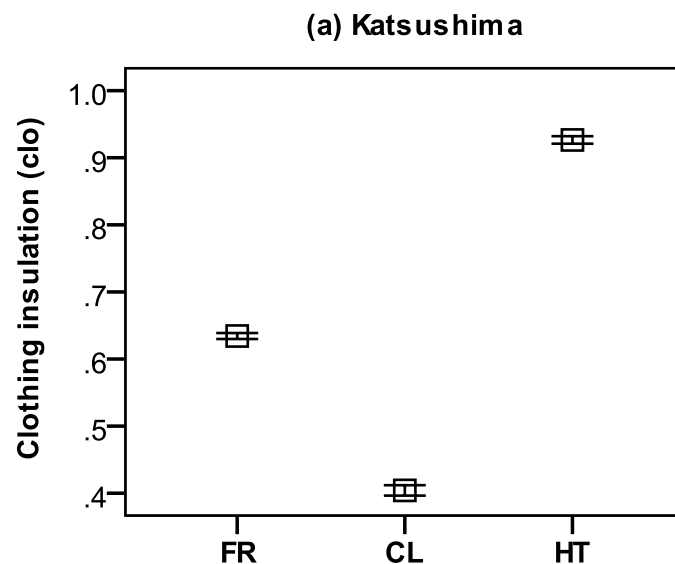


Figure 6.9 Mean clothing insulation in different modes

Figure 6.10 shows male and female clo values. The female clo value is observed higher than male in all the summer and winter months except August. August was observed the hottest month of the year and in this month, the male and female clo value is overlapped. It must be due to the high indoor air temperature, which resulted in similar clo values between male and female.

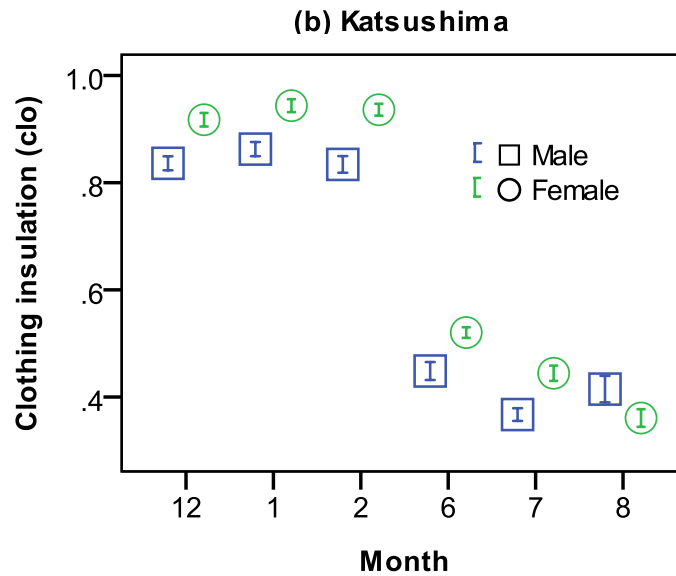


Figure 6.10 Male and female clothing insulation in summer and winter

The male and female clo values during summer and winter in this condominium is different from other studies as shown in Table 6.1. The clo value in Tokyo office study higher in summer and lower in winter than this study and Nagoya school is higher in summer and winter than this study. The reason could be due to the dress code and more number of people staying together in the office. In school which might have created warm environment due to the poor insulation and solar controlled to clothing insulation smaller than the clo values in HEMS condominium. The residential buildings and detached houses of Gifu area [7] have lower clo values than this study in summer. The reason might be due to poor insulation and solar control resulting high indoor air temperature during summer and the occupants might have adjusted with a lower clothing insulation. The clothing insulation values in Fukuoka are higher than this study in both summer and winter.

The males were found spending more time for exercise and maybe due to this reason their clothing insulation is slightly lower than female. August was observed the hottest month of the year and in this month, the male and female clo value is overlapped. It might be due to the high indoor air temperature, which might have led them to use cooling and resulted similar clothing insulation between male and female.

The residential buildings and detached houses of Gifu area [7] have lower clothing insulation than this study in summer but female clothing insulation in winter is lightly

higher than this study. The reason might be due to poor insulation and solar control resulting high indoor air temperature during summer and the occupants might have adjusted with a lower clothing insulation. In winter, due to good insulation in this building might have resulted warm indoor environment leading lower clothing insulation than Gifu area. The clothing insulation values in Fukuoka [10] are higher than this study in both summer and winter. Low clothing insulation might have helped the occupants of this condominium to adjust thermal comfort during high indoor air temperature. The overall clothing insulation analysis result showed that the clothing insulation was different according to seasons, months and gender wise.

Table 6.1 Comparison of clothing insulation with other studies

Reference	Studied buildings	Area	Summer		Winter	
			Male	Female	Male	Female
This study	HEMS condominium	Tokyo	0.41	0.46	0.84	0.93
Osamu et al.	-	Fukuoka	0.65	0.58	1.05	1.07
Takashi et al.	Office buildings	Tokyo	0.65	0.56	0.81	0.76
Suzuki et al.	School buildings	Nagoya	0.43	0.46	1.03	1.28
Watanabe et al.	Residential buildings and detached houses	Gifu	0.32	0.38	-	-

## 6.5 Relations of clothing insulation with thermal sensation

We observed the relation between clothing insulation and thermal sensation votes as shown in Figure 6.11. We found very low relation between clothing insulation and TSV votes. The clothing insulation value is different in different seasons even with the same neutral TSV that is 4. So, we can say that there is no significant relationship between clothing insulation and thermal sensation.

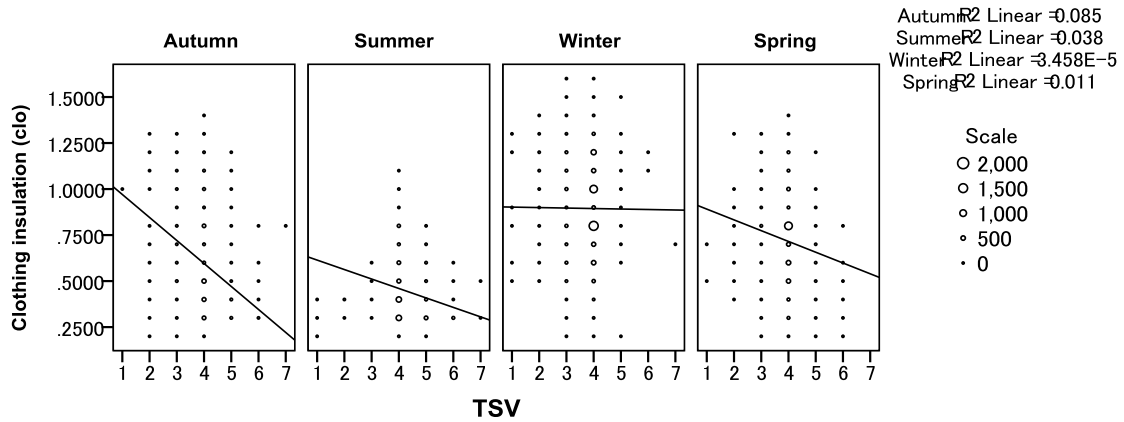


Figure 6.11 The relation between clothing insulation and thermal sensation

## 6.6 Relations of clothing with outdoor and indoor air temperature

In order to predict the clothing insulation, we did regression analysis of clothing insulation (I<sub>cl</sub>) with outdoor air temperature (T<sub>o</sub>) and indoor air temperature (T<sub>i</sub>) in FR mode. Figure 6.12 and Figure 6.13 show the relationships between clothing insulation and outdoor and indoor air temperature respectively. The lines of regressions were expressed as follow.

$$I_{cl} = -0.023 T_o + 1.05 \quad (n=9510, R^2=0.431, S.E. = 0.001, p < 0.001) \quad (6.1)$$

$$I_{cl} = -0.049 T_i + 1.95 \quad (n=6538, R^2=0.421, S.E. = 0.001, p < 0.001) \quad (6.2)$$

where, n is number of votes; R<sup>2</sup> is the coefficient of determination; S.E. is standard error of regression coefficient (°C), p is the level of significance for the regression coefficient.

The linear regression lines are statistically significant because of a large number of data. As the temperature increases, the clothing insulation decreases. 1.0 clo corresponds to 2°C of outdoor air temperature and to 18°C of indoor air temperature, 0.4 clo corresponds to 30°C of outdoor air temperature and 31°C of indoor air temperature. We observed the clothing insulation differences of high and low temperature groups as well. Mostly, in any dwelling there might be clothing insulation differences due to individual perception for thermal comfort adjustments. We here, tried to evaluate the clothing insulation differences of the groups maintaining high and low temperature in summer and winter.

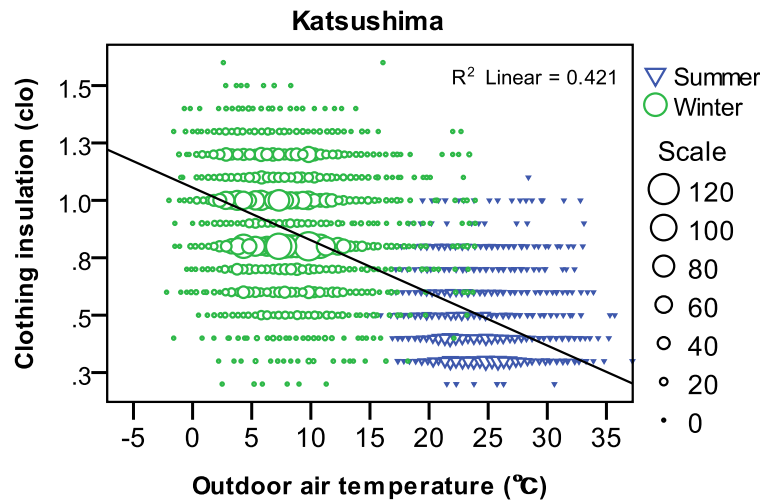


Figure 6.12 Relation between clothing insulation and outdoor air temperature

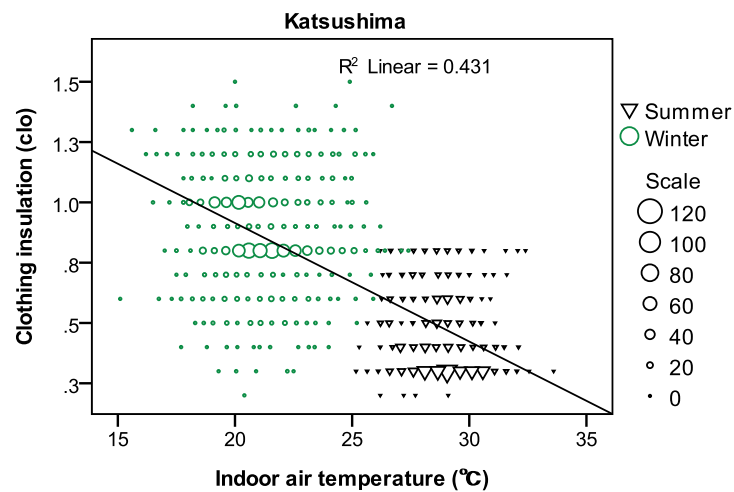


Figure 6.13 Relation between clothing insulation and indoor air temperature

Figure 9.14 shows the clothing insulation between SH and SL in summer in FR mode. The occupants of both groups were observed adjusting thermal comfort with low clothing insulation in summer. Comparatively, SH has slightly lower clothing insulation than SL.



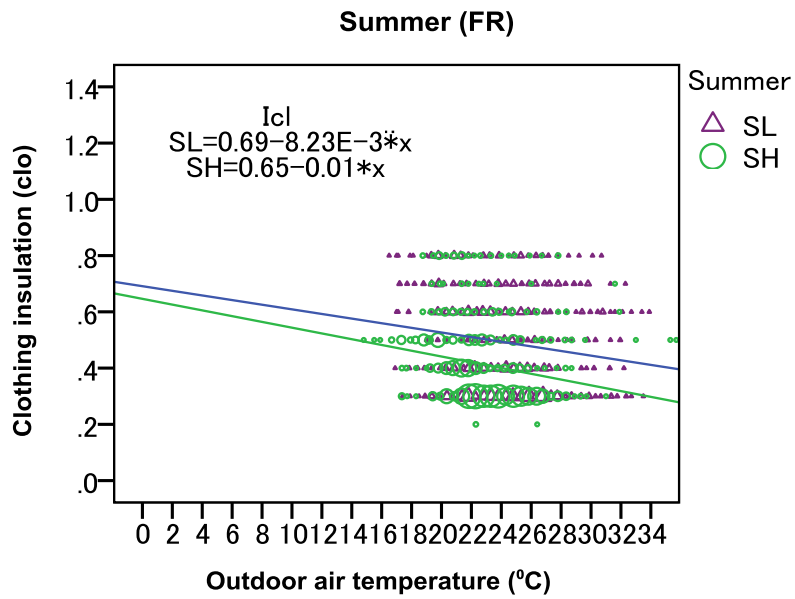


Figure 6.14 Clothing insulation difference of high and low group in summer

Figure 6.15 shows the clothing insulation differences of WH and WL in winter in FR mode.

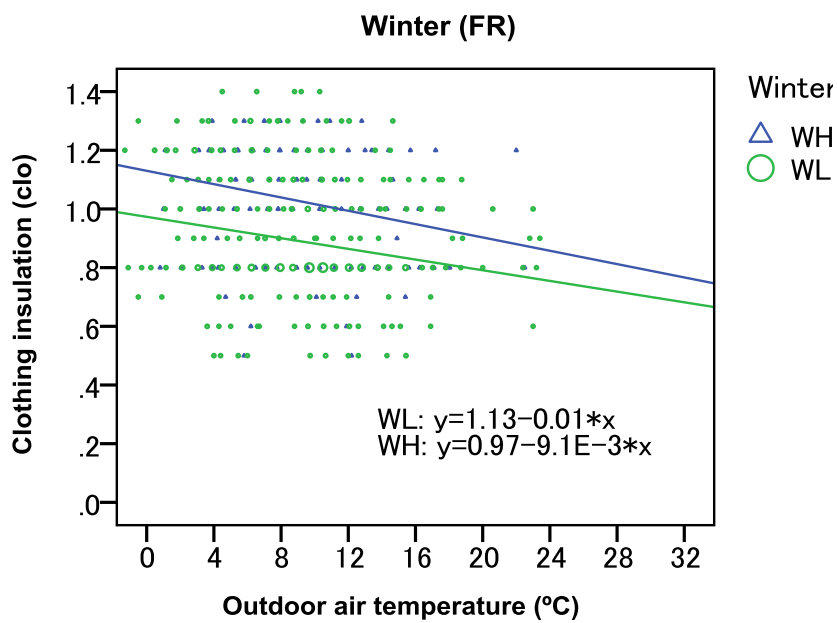


Figure 6.15 Clothing insulation difference of high and low group in winter

Interestingly, the occupants of WH have slightly higher clothing insulation than WL. Probably, WH might prefer higher temperature and need more heating if they use low clothing insulation. But the difference in clothing insulation between high temperature group and low temperature group is not so large.

## 6.7 Fan use

We tried to analyze how the occupants have adapted to the thermal environment represented by higher indoor temperature. As shown in Figure 6.16, a large proportion of the occupants were using fan when the indoor air temperature is above 28°C.

As the indoor air temperature increased the proportion of the occupants using fan also increased. Possibly, this behavior of the occupants must have helped them to adjust thermal comfort even for the condition of high indoor air temperature. When the indoor air temperature is 30 °C, 0.4 proportion of occupants were using fan in FR mode. Even 0.10 proportion of occupants used fan in CL mode when the indoor air temperature is equal to 30 °C. Possibly, the fan used in CL mode for the smooth flow of the air of air conditioning unit.

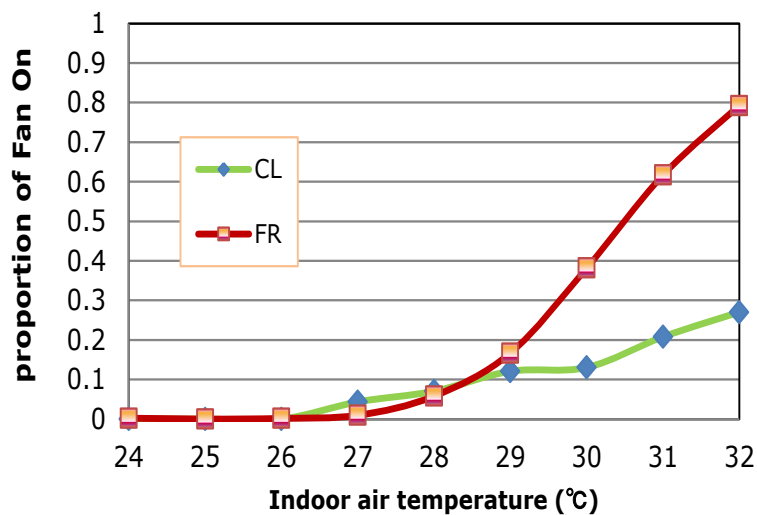


Figure 6.16 the relation of fan use and indoor air temperature in FR and CL mode

Figure 6.17 show the monthly mean proportion of fan use in summer months. In August, the proportion of fan use is observed highest which is equal to 0.48 in FR mode.

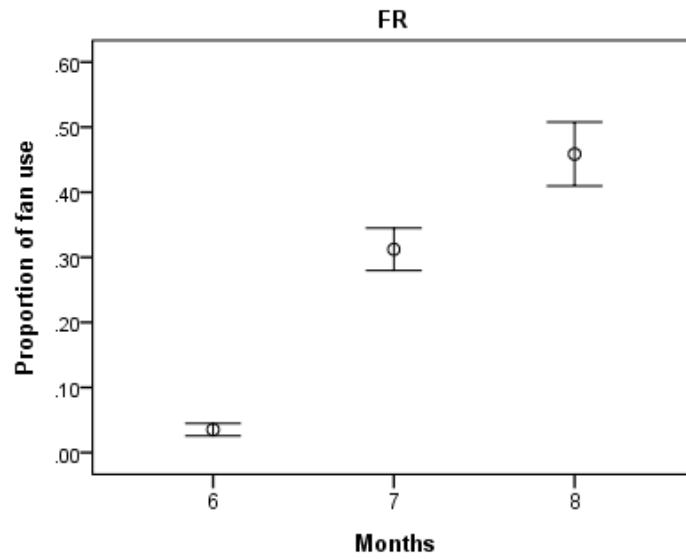


Figure 6.17 Proportion of fan use in summer months

We observed the proportion of fan use of two high and low temperature groups. Figure 6.18 shows that the fan use increased along with outdoor air temperature for both SH and SL group.

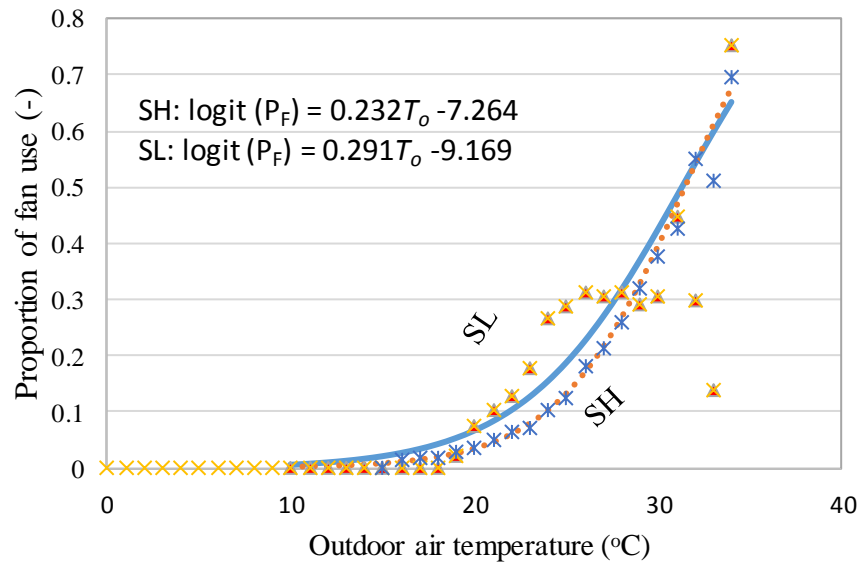


Figure 6.18 Proportion of fan use of high and low group.

The occupants used fan rather than air conditioning units for adjusting thermal environment when the outdoor air temperature is low. The proportion of fan use is

almost similar for both SH and SL group. As the outdoor air temperature is above 27°C, the proportion of fan use sharply increased for both SH and SL.

Rijal et al. [12] found that there is almost 2 °C difference in comfort temperature between fan on and fan off conditions as shown in Figure 6.18. We have observed that a large proportion of the occupants living in the studied building were using fan. This behaviors of the occupants might have definitely helped the occupants to feel comfortable with high indoor air temperature.

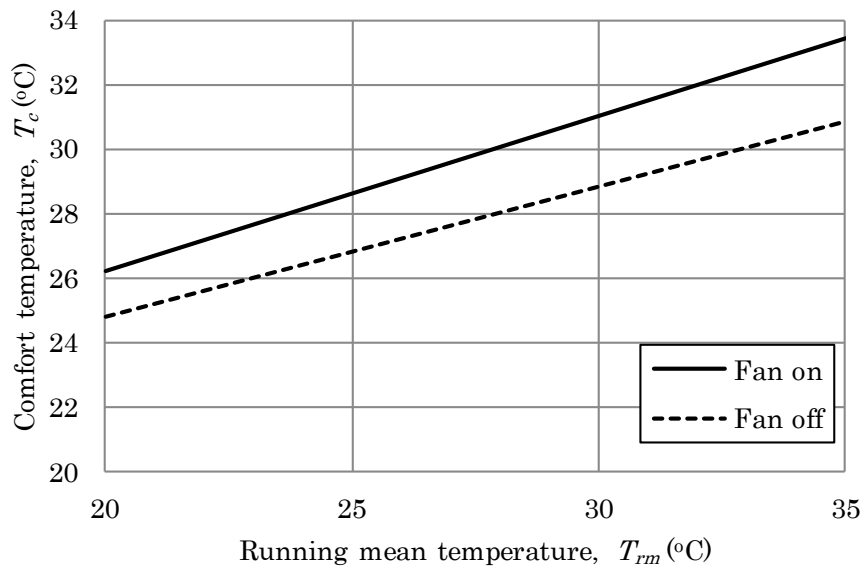


Figure 6.19 Relation between comfort temperature and fan on and fan off [12]

### 6.8 Cooling use

Although, the active cooling is significant however; the overall performance of the active cooling is heavily climatic dependent and may not be enough to satisfy the proper indoor comfort requirements under all climatic conditions [13]. Under such circumstances the use of mechanical cooling is necessary to adjust indoor temperature for thermal comfort. The use of air-conditioning cooling was observed in this building to know how the occupants have adjusted the thermal comfort in summer. Figure 6.20 showed that the percentage of air conditioning unit use increased as the temperature increased in July and August. August is the hottest months of summer. So the highest percentage of the occupants has been using cooling during this time. Out of the total

number of votes received for cooling use in summer, 45.60% have used mechanical cooling at the time of voting.

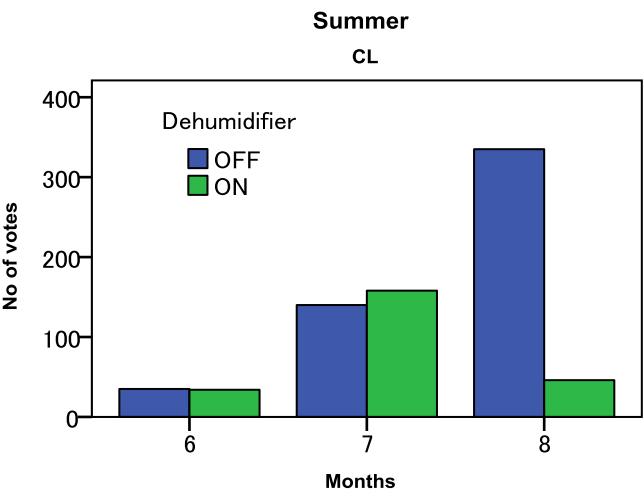


Figure 6.20 Percentage of air conditioning cooling on and cooling off.

As shown in Figure 6.21, the proportion of air conditioning unit for cooling use increased as the mean outdoor air temperature increased. When the mean outdoor air temperatures are 25.7and 31.3°C, the proportion of AC users are 15% and 42% respectively.

We observed the use of air conditioning unit for cooling of both high and low temperature groups. The use of cooling increased with high outdoor air temperature increase. The occupants used air conditioning units for cooling when the outdoor air temperature is high.

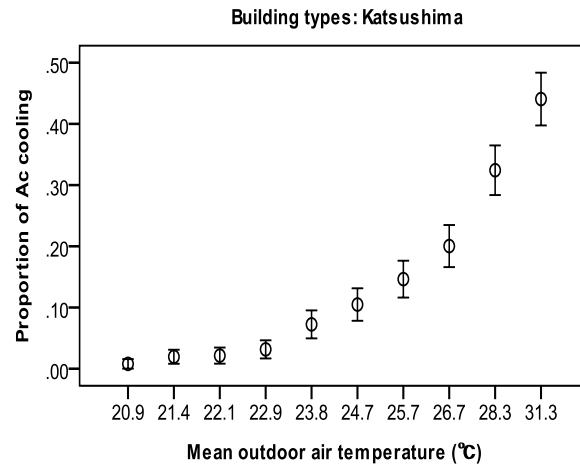


Figure 6.21 Relation between outdoor air temperature and cooling use

Figure 6.22 shows that the occupants used cooling only with high outdoor air temperature. The occupants used air conditioning units for cooling when the outdoor air temperature rises higher than 25°C but the rate of increase is not large up to 26 °C for both SL and SH. With high outdoor air temperature, the cooling use for SH is less than SL. The proportion of cooling use for SL reached 0.30 at outdoor air temperature at 27 °C. This is about 0.20 lower than a previous study done in Gifu area of Japan which is 0.50 [7]. This might be due to mean radiant temperature in this condominium being lower than that of the detached houses in Gifu area with rather low insulation level, as suggested by a human-body exergy research [15, 16].

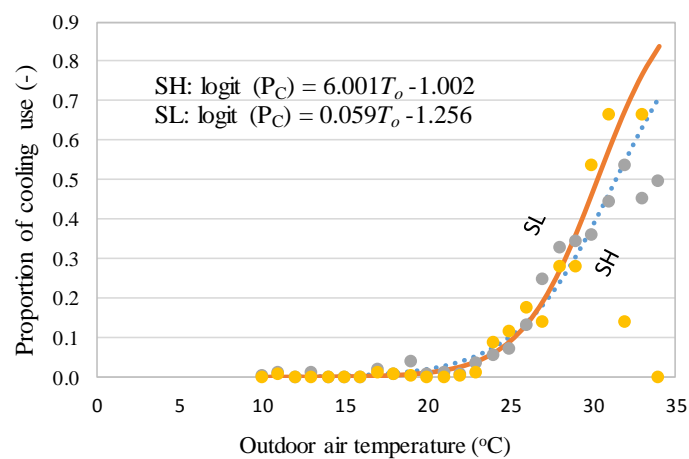


Figure 6.22 Cooling use of high and low temperature group.

## 6.9 Heating use

When outdoor environment is very cold there may be need of heating to improve the indoor thermal environment. Under such circumstances the use of mechanical heating is necessary to adjust indoor temperature for thermal comfort. The use of different means of heating was observed in this building to know how the occupants have adjusted the thermal comfort in winter.

### 6.9.1 Use of air conditioning unit for heating

The occupants want to be comfortable in the variety of conditions using heating. In very cold time, it may be too hard or inefficiently to maintain the comfort of a consistent air temperature. Heat is required for thermal adjustment. Figure 6.23 shows the percentage of heating use in winter months. Almost 34% of the total votes received in winter mentioned that they had been using heating in January.

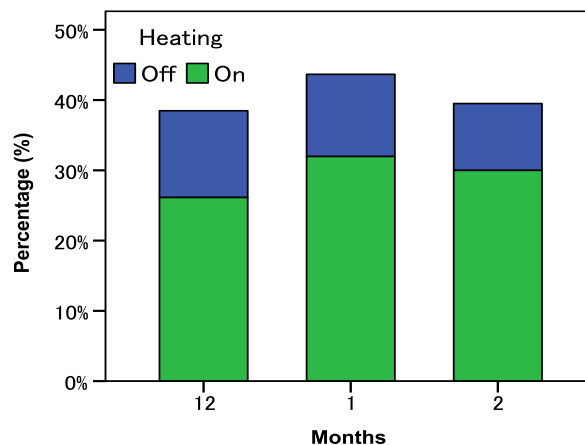


Figure 6.23 Heating use in winter months

Figure 6.24 showed that the use of heating increased as the mean outdoor air temperature decreased. Under the condition of the outdoor air temperature is below 10°C, around 25 to 30% proportion of the occupants were using heating.

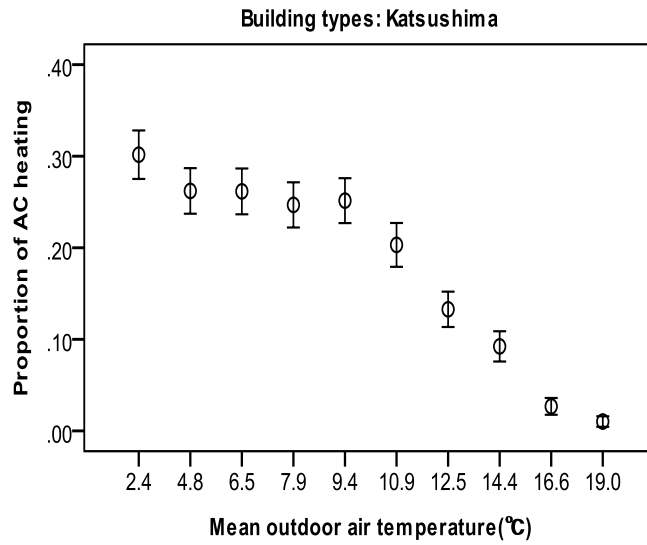


Figure 6.24 The relation between outdoor air temperature and heating

We observed the use of air conditioning unit for heating of both high and low temperature groups. The use of heating increased with low outdoor air temperature. Figure 6.25 shows the proportion of heating use for WH and WL groups.

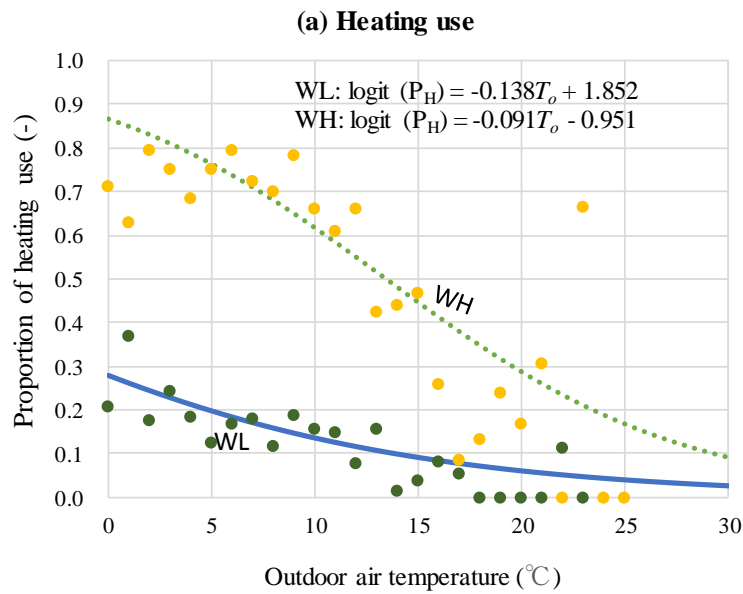


Figure 6.25 Heating use of high and low temperature groups in winter



The proportion of heating use for both WH and WL gradually increases as the outdoor air temperature becomes lower than 20°C. The proportion of heating use for WH is higher than WL. The proportion of heating use for WH is 0.85 when the outdoor air temperature is 0°C but the proportion of WL is only 0.29 when the outdoor air temperature is 0°C. The trend of heating use of WH is almost similar to the study done in detached houses of Tokyo, Yokohama and Chiba areas of Japan that was 0.90 [17] but the proportion of heating use of WL is much lower. It is probably due to better level of thermal insulation in this condominium comparing to that of other Japanese condominium and detached houses.

### 6.9.2 Floor heating

The percentage of floor heating was observed to understand the trend of floor heating use. Figure 6.26 shows the floor heating setting. The result showed that mostly setting 3, 4 and 5 are used for floor heating. Comparatively, 3, 4 and 5 are the lower limit of setting. Maybe, the occupants were conscious about energy saving so they used the lower setting of floor heating.

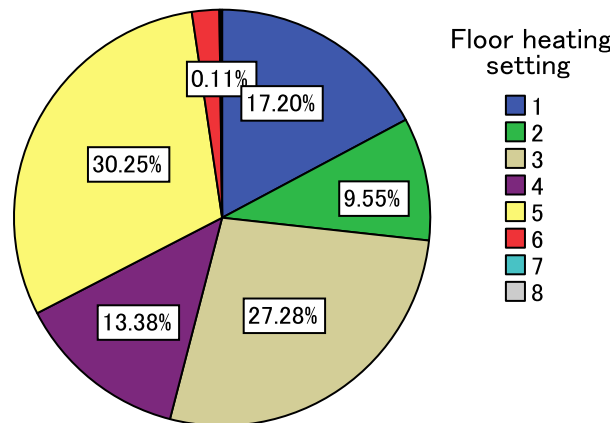


Figure 6.26 Setting for floor heating

### 6.9.3 Kotatsu use

Kotatsu is a traditional heating device in Japan. Among the heating devices 27.54% proportion was Kotatsu use. We have checked the number of data for Kotatsu use in

terms of the outdoor air temperature. We found very less number of data above 16°C. We excluded the data below the number 10 and analyzed.

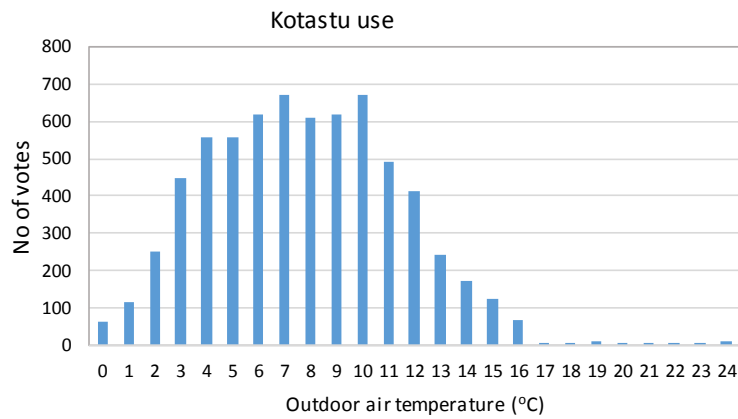


Figure 6.27 Number of votes for Kotatsu users for outdoor air temperature

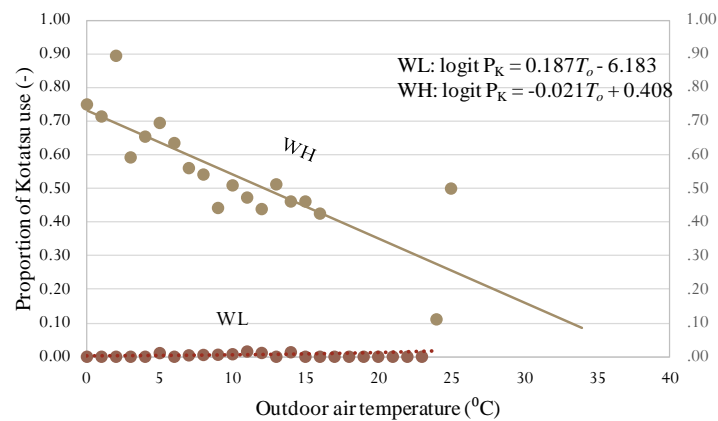


Figure 6.28 Proportion of Kotatsu use for given outdoor air temperature

This system is quite popular in Japan and commonly used in most of the residences. We observed the Kotatsu use of two groups with high and low indoor air temperature. As shown in Figure 6.28 the proportion of Kotatsu use for WH is high; it is equal to 0.60 when the outdoor air temperature is 0°C. But the use of Kotatsu for WL is almost none.

### 6.10 Relation between behaviors and indoor air temperature.

We observed the relation of heating use and clothing insulation in terms of the observed indoor air temperature. As shown in Figure 6.29.

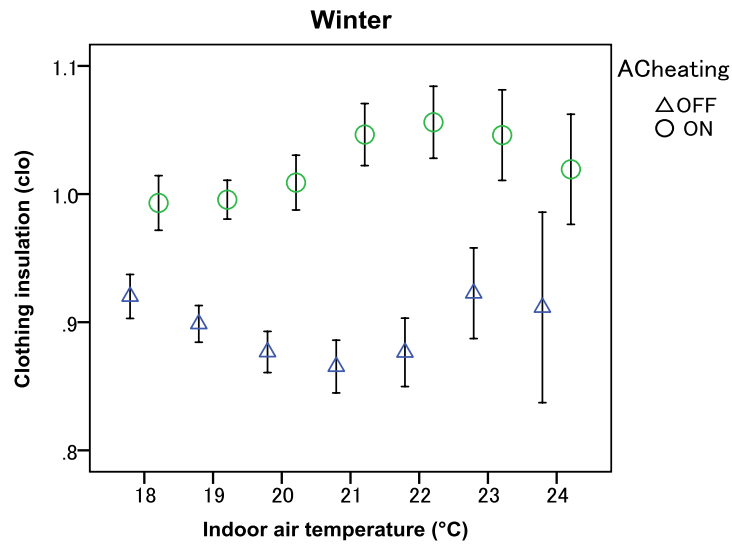


Figure 6.29 The relation of clothing insulation, heating use and indoor air temperature

we found that when heating is used, the clothing insulation is also high. Possibly, the occupants used high clothing insulation along the use of heating. Our result showed that if the occupants do not use high clothing insulation, they might have to increase the use of heating more than that.

## 6. 11 Conclusions

From the analysis of occupants' behaviors in a condominium equipped with HEMS, we obtained the following result.

1. The window opening, fan use, cooling and heating behaviors of the families living with HEMS systems for thermal comfort adjustments were not similar even living with HEMS system in a same condominium. The window opening behaviors of the occupants is high in June and July if compare to August. A high proportion of the occupants adjusted thermal comfort in passive mode.
2. The use of fans is equally used for thermal adjustment.
3. The clothing insulation highly influenced by outdoor temperature. The clothing trend is similar to other studies.
4. The cooling is used when the outdoor air temperature is above 20°C. The large proportion used cooling when the outdoor air temperature is 31.7°C.

5. The heating was used when the outdoor air temperature is below 20°C. When outdoor air temperature is below 10°C, the large proportion of heating is observed.

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# **Chapter 7: Conclusions and Recommendation**

## **7.1 Conclusions of Chapter 3**

Researchers in HEMS sectors found that users tend to ignore energy monitoring HEMS after certain period. Some applicable apps can be added with HEMS software that could attract or motivate people towards regular use of the HEMS technology. For example, if some health related apps are included which could provide health tips and help the users to remain healthy and fit, they could use it regularly. Users may like apps that provided convenient feedback to help them monitor, track and review attempts to change or improve health behavior. So HEMS should be developed into adaptive technology which would focus the sustainable behaviors of the users towards energy saving. Then only, HEMS use seems to be uniformly and long lasting. From the review of the previous researches done on the HEMS and energy management, the present status of global HEMS market and the increasing scope of HEMS globally and in Japan were observed and also the thermal comfort level of HEMS-managed residential buildings located in Tokyo Japan was identified. We obtained the following result from this study. It has been understood that energy saving and cost saving is possible with the use of HEMS in buildings. In HEMS buildings so far 17.9 % of energy saving and 8.9% of cost saving is possible if it is effectively applied. HEMS developed so far is not strong enough to focus the behaviors of the occupants so that there is not uniformity in energy saving between the HEMS users. Some apps related to the adaptive behaviors that might be useful in everyday life and that attract the attention of the users regularly should be included with HEMS in the future.

## **7.2 Conclusions of chapter 4**

The overall result showed monthly and seasonal differences in indoor air temperature and relative humidity. The indoor air temperature in the studied condominium was different to seasons, floors and flats. Even the building was equipped with HEMS systems, there is large range of temperature variation in indoor thermal environment due to individual adaptive activities of the occupants similar to common detached houses and residential buildings. The amount of water vapor concentration is different by families. The amount of water vapor concentration increased by 2-2.5gm<sup>3</sup> in every

10-15% increase in indoor relative humidity. The amount of water vapor concentration increased as the indoor air temperature increased. The occupants felt the indoor environment more humid when the amount of water vapor concentration increased. The indoor water vapor concentration has been influenced by outdoor water vapor concentration. When outdoor air temperature is high, the amount of water vapor concentration increased. The occupants felt neither humid nor dry between the ranges of 40-60% of relative humidity. The indoor air temperature in the studied condominium was observed dependent on outdoor air temperature in FR mode. The occupants mostly take FR mode rather than CL and HT modes. The mean indoor air temperature in winter was around 20 °C which is similar even in FR mode. This is due to the thermal insulation level being rather better than conventional houses in Tokyo area. In CL mode, the mean indoor air temperature is 27.9 °C which is similar to the recommended indoor air temperature equal to 28 °C in summer in Japan. The indoor air temperature in the studied condominium was not similar according to seasons, floors and flats. Even the building was equipped with HEMS systems, there is large range of temperature variation in indoor air temperature due to individual adaptive activities of the occupants similar to common detached houses and residential buildings. There is 2 °C difference between SH and SL in summer and 4 °C difference between WH and WL in winter. It shows that the behavioral characteristics of these four groups are different even using the same HEMS systems. The indoor air temperature and relative humidity measured in the respective flats in the studied building was observed dependent on the outdoor environment as the indoor environment changed according to months and seasons. Even with smart living the indoor thermal environment is different per family which indicates the importance of individual perception for any kinds of guidelines or model.

### **7.3 Conclusions of chapter 5**

The level of indoor thermal comfort is high. The thermal sensation votes were mostly neutral in all modes. The large numbers of votes in terms of preference was 'no change' in both summer and winter seasons. Very few were found to prefer change. The TSV were observed related to the occupants' preference of 'preferring cooler' and 'preferring warmer'. The maximum proportion of comfort was equal to 22.8 °C of indoor air temperature. The proportion of 'comfort' at more than 90% was 27.5 °C for the higher temperature and 18 °C for lower. The thermal sensation votes were mostly neutral in all modes. The large numbers of votes in terms of preference was 'no change' in both summer and winter seasons. Very few were found to prefer change. The TSV votes

were observed related to the occupants' preference of 'preferring cooler' and 'preferring warmer'. The maximum proportion of comfort is equal to 22.8 °C of indoor air temperature. The proportion of 'comfort' gradually decreases below or above this optimum temperature but the proportion of 90% ranges. The thermal preference of the occupants is different according to the modes and temperature differences, which proves that the occupants performed various adaptive behaviors in different seasons. The thermal perception also changed according to temperature differences. The humidity sensation and skin moisture perception was also different in different modes.

Every human has an adaptive opportunity to create their own mini thermal environment. So, they perform various activities which might be similar or different than others. There will be the differences in behaviors and the time of involvement for various active and passive activities. Similar types of result will be obtained if similar survey is conducted in different areas. But the result may have the differences as the indoor environment is affected by outdoor environment. The result may have numerical differences depending on the outdoor air temperature if similar types of the survey is conducted in other areas. This information should be considered in thermal comfort standard. Though I have not analyzed the effect of history on comfort and comfort temperature.

#### **7.4 Conclusions of chapter 6**

Generally, people use passive and active means for adjusting thermal comfort. It was expected that the occupants were fully using mechanical means for thermal comfort adjustments. But the result showed that the occupants were very active using passive means as well for thermal comfort adjustment. The window opening, fan use, cooling and heating behaviors of the families living with HEMS systems for thermal comfort adjustments were not similar in a same condominium. The occupants were observed using passive means first then active means. The window opening behaviors of the occupants is high in June and July if compare to August. A high proportion of the occupants adjusted thermal comfort in passive mode. The use of fans is equally used for thermal adjustment. The clothing insulation highly influenced by outdoor temperature. The clothing trend is similar to other studies. The cooling is used when the outdoor air temperature is above 20°C. The large proportion used cooling when the outdoor air temperature is 31.7 °C. The heating was used when the outdoor air temperature is below 20 °C. When outdoor air temperature is below 10°C, the large proportion of heating is observed.



## **7.5 Recommendation**

The indication of electricity use by HEMS might encourage occupants to think about the cost and energy saving. HEMS should be improved, providing alternative means for taking different adaptive opportunities. HEMS should provide people with an opportunity to be freer in adapting various activities so that they can adjust their thermal comfort as they like. Some development of software to be used in smart phones related to such occupants' behaviors may be one possibility to be included with HEMS so that the users pay more attention for the use of HEMS. Mechanical controls tend to be considered for the only way of thermal comfort, but in reality it was found that the occupants take various other behaviors to adjust their thermal environment. Therefore, HEMS should also include occupants' adaptive behaviors to be taken indoors and provide with some useful information. Additional software that provides information about the right situations for taking passive means such as window opening, or the use of cooling or heating, needs to be included with HEMS so that the system will be more efficient for use in the future. HEMS should also be able to provide with alternative means such as when outdoor environment is good for taking natural ventilation. HEMS should provide the people with an opportunity to be freer so that they could adjust their thermal comfort as they like. If the information of appropriate timing for window opening or closing in relation to outdoor air temperature, right timing for the use of passive means and active means of thermal adjustment and others are displayed along with the information of electricity use at home, the HEMS system will be more effective to be used in the future.

The adaptive thermal comfort standard needs to be developed considering the occupant's behavioral adaptation as well.

## **Publications**

### **Journals**

1. KC Rajan, Rijal H.B., Yoshida K., Shukuya M. 2016. Feasibility study on the use of HEMS for thermal comfort and energy saving in Japanese residential buildings, International journal of civil, environmental, structural, construction and architectural engineering Vol:10, No:9, pp. 1091-1097.
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### **International conferences**

- 1 KC Rajan, Rijal H.B., Yoshida K., Shukuya M. Feasibility study on the use of HEMS for thermal comfort and energy saving in Japanese residential buildings ICAAEBS, 18th International Conference on Advanced Architectural Engineering and Building Services. Conference proceedings, Singapore SG Sep 08-09, 2016, 18 (9) Part IV, pp. 443-449 (Conference).
- 2 KC Rajan, Rijal H.B., Shukuya M., Yoshida K., A study on indoor air temperature and thermal comfort in HEMS condominium". 17th Conference of Science Council of Asia in Philippine. 14-17th June 2017 (Conference).
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### **National conferences and symposium**

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