PhD THESIS

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Study on the Utilization of Sun Heat in Air Layer Attached to External Wall of a House with Central HVAC System

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Abstract

With the promotion of highly insulated and sealed houses, the central air conditioning systems that integrate ventilation, cooling and heating have received attention. In addition, solar heat utilization is attracting attention as an effective means to reduce energy consumption of cooling/heating and hot water supply. Therefore, research and development of houses combining the central air conditioning system and solar energy utilization are necessary for a comfortable thermal environment and energy saving. One of the easiest and cheapest methods of using solar energy is to add an air layer to the external walls. There are different types of external wall systems which contain air layers, such as the sunspace, double skin facade, Trombe wall, etc.

In the thesis, we conducted an actual survey to understand the situation of heat utilization of the air channel and used numerical simulations to examine the effective method of heat utilization of the air channel. To reduce the heating load, during the heating period, the heat from the air channel of the sunspace, Trombe wall, and DSF is sent to the central air conditioning room, from where it is then distributed and stored throughout the building by way of air circulation. Further, during the cooling period, the cooling load can be reduced by opening the windows on the outside of the sunspace and using the roof and wing walls to provide shade from the sun. The experimental work introduced here mainly focuses on the analysis of the performance of the sunspace, when the air is sent to the central air conditioning room from the air channel of the sunspace. The sunspace is located on the south side of the house with a central air conditioning and air circulation system. The house in Miyazaki, Japan. We ran numerical simulations using THERB for HAM software to investigate effective methods of using the heat from inside the air channel (sunspace, DSF and Trombe wall), as well as possible structural improvements. We also conducted the energy performance comparison between a sunspace, double skin facade and Trombe wall.

The thesis consists of eight chapters and the summary of each chapter is shown as follows.

In the chapter 1, background, previous research, objectives, purposes, and configuration of the thesis are described.

In the chapter 2, an overview of the demonstration house and simulation conditions.

In the chapter 3, we conducted an actual survey to understand the situation of heat utilization of the sunspace and used numerical simulations to examine the effective method of heat utilization of the sunspace.

In the chapter 4, we conducted an actual survey of the thermal environment for demonstration houses in Miyazaki city and analyzed the thermal environment of each room.

In the chapter 5, the main purposes of this chapter are to identify heat collection effects and heating load reduction effects of a sunspace structure based on numerical simulation by examining efficient heat utilization methods within a sunspace and floor plans in winter.

In the chapter 6, numerical studies on the energy performance of the sunspace, DSF (double skin facade) and Trombe wall were carried out.

In the chapter 7, we clarified the thermal environment of each room during heat utilization of the sunspace, double skin facade and Trombe wall and examined whether it is possible to maintain thermal environment suitable for daily behavior.

In the chapter 8, the results of the thesis are summarized.

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Chapter 1.

Introduction

1. Introduction

1.1. Background

With the growing awareness of global warming and people need for comfortable indoor environment and building energy saving design, the utilization of energy has become a vital issue and the conservation of energy has acquired prime importance. Building energy consumption accounts for a great part of regional and global energy needs. Parts of the major energy consumption in buildings are the heating, ventilating, and air conditioning (HVAC) systems. They are indoor climate controls that regulate humidity and temperature to provide thermal comfort and indoor air quality [1].

Building energy consumption for cooling and heating accounts for 18–73% of overall energy consumption. Heating energy consumption occupies 32–33% of the overall building energy consumption [2]. Japan's buildings consume more than 30% of its energy consumption [3]. In recent years, standards for energy saving have been reviewed as the awareness of energy and global warming grows. Accordingly, measures for improving thermal insulation, energy generation, and efficient energy usage in houses are considered important. Their purpose is to realize a 10% increase in the ratio of renewable energy per primary energy supply by 2020, through promoting solar energy and solar light [3]. The use of solar design for achieving thermal comfort inside a building is a growing concern world over for the building energy conservation [4]. The solar techniques can reduce yearly heating requirement by 25% [5]. The optimal architectural design strategies could save 63% to 76% of energy [6].

With the promotion of highly insulated and sealed houses, the central air conditioning systems that integrate ventilation, cooling and heating have received attention. In addition, solar heat utilization is attracting attention as an effective means to reduce energy consumption of cooling/heating and hot water supply. Therefore, research and development of houses combining the central air conditioning system and solar energy utilization are necessary for a comfortable thermal environment and energy saving.

1.2. A house with a central heating, ventilation, and air conditioning system

Figure 1.1 shows a house with a central heating, ventilation, and air conditioning system. External air is sent to the central air conditioning machine room through air filters and a total heat exchanger. The air in the central air conditioning machine room is then sent to each room after its temperature and humidity are adjusted by a residential heat pump air conditioning unit. The air in the rooms returns to the central air conditioning machine room through vent layers in the wall and duct. Part of the air is discharged to the outside by a total heat exchanger. The rest of the air is sent back to the rooms after going through the central air conditioning machine room again.

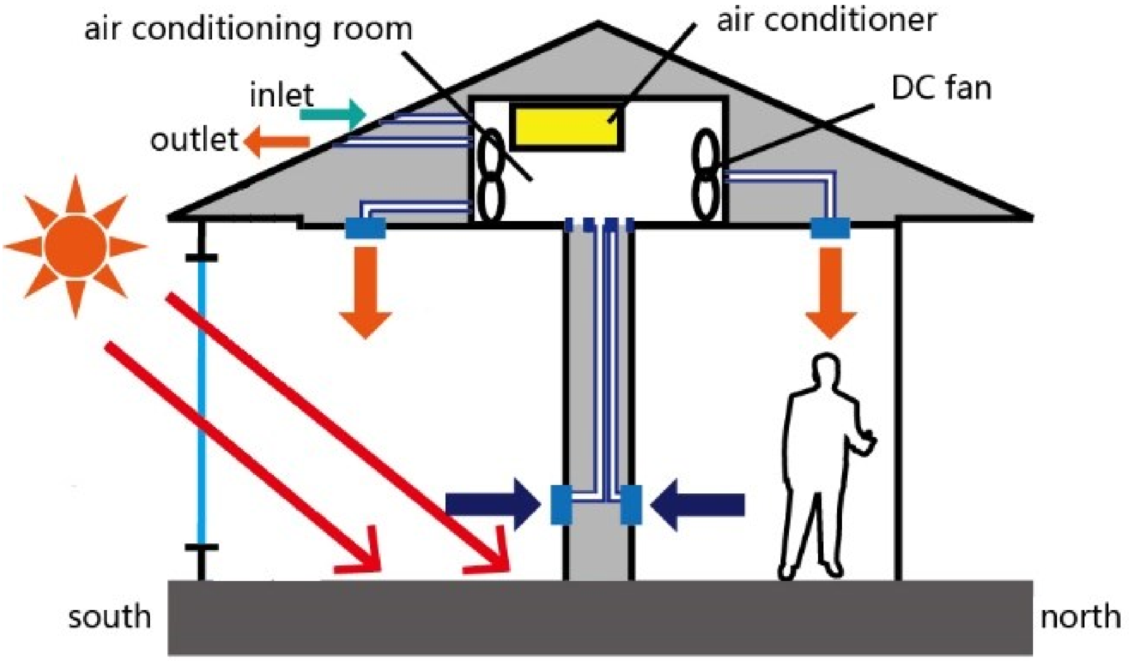

Figure 1.1 A house with a central heating, ventilation, and air conditioning system

1.3. Solar energy utilization systems

One of the easiest and cheapest methods of using solar energy is to add an air layer to the external walls. There are different types of external wall systems which contain air layers, such as the sunspace, double skin facade, Trombe wall, etc.

Figure 1.2 shows the combination of the sunspace and central air conditioning system. The sunspace is considered for the heating season as they capture the maximum sunlight coming in through the glazing surface causing the inner wall surfaces and air to increase their temperatures [7]. The sunspace consists of a transparent glazing panel, the air channel, and the inner wall with additional windows. Figure 1.3 shows the combination of the double skin facade and central air conditioning system. The double skin facade (DSF) refers to a building façade covering one or more levels with multiple glazed skins. The cavity between the skins of the façade can be airtight or naturally/mechanically ventilated. Application of an air-tightened DSF increases the building thermal insulation while reducing the heat loss during winter [8]. Figure 1.4 shows the combination of the Trombe wall and central air conditioning system. Trombe wall consists of a transparent glazing panel, the air channel, the vent, and the storage wall [9]. Solar heat is stored by the storage wall during the day and released into the room at night.

To reduce the heating load, during the heating period, the heat from the air channel of the sunspace, Trombe wall, and DSF is sent to the central air conditioning room, from where it is then distributed and stored throughout the building by way of air circulation. Further, during the cooling period, the cooling load can be reduced by opening the windows on the outside of the sunspace and using the roof and wing walls to provide shade from the sun.

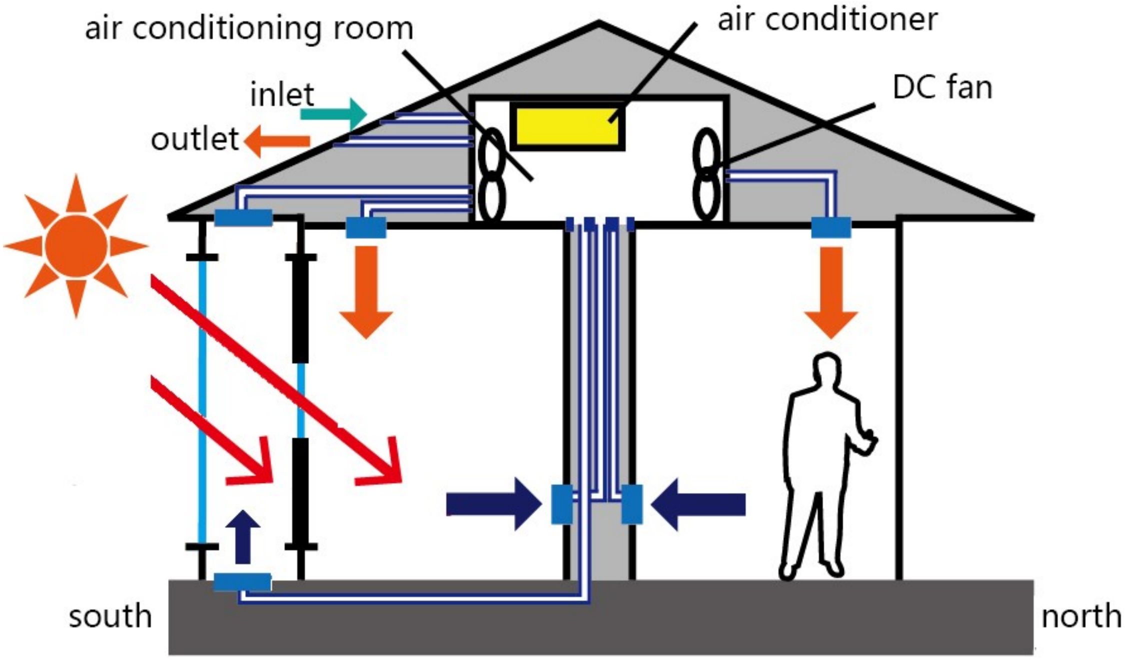

Figure 1.2 The combination of the sunspace and central air conditioning system

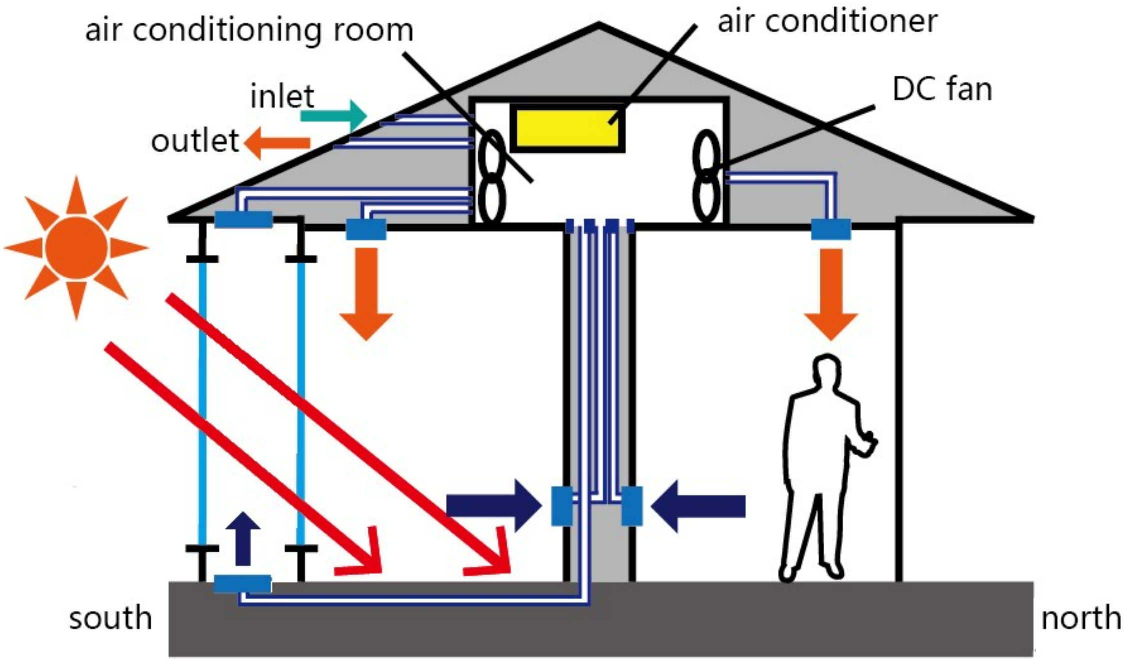

Figure 1.3 The combination of the DSF and central air conditioning system

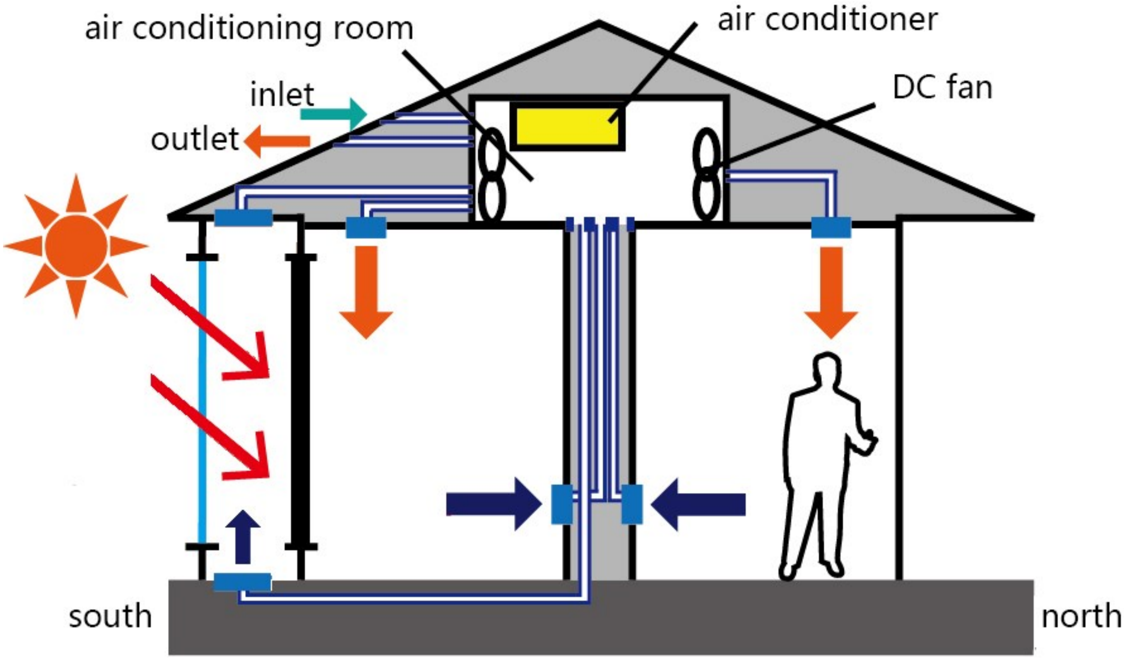

Figure 1.4 The combination of the Trombe wall and central air conditioning system

1.4. Literature review

1.4.1. Sunspace

Many scholars studied various components to help improve the efficiency of sunspaces such as glazed types, glazed area, the dimension and form of sunspaces, shading devices, ventilation, orientation, and the storage wall's materials.

Bakos, G.C. [10] investigated the energy and economic performance of a conventional dwelling with an attached sunspace located in northern Greece. The results showed that the optimum heat-gathering area was about 13.75 m^2, which can save 18% of the annual thermal energy. Mihalakakou, G. [11] studied the cooling/heating ability of buildings equipped with sunspaces in Milan, Dublin, Athens, and Florence. The results showed that sunspaces can reduce heating thermal energy in winter, but cause severe overheating problems in summer. The problem of overheating can be solved by using three passive cooling technologies (shading devices, night ventilation and buried pipes). Lu, S. [12] studied the energy consumption of a building with a PCM (phase change material) wall attached with a sunspace and a PCM radiant floor system. The results showed that in the active control phase, the investigational room energy saving rate was 54.27% compared to the traditional room. In the passive energy-storage phase, the traditional room temperature was 7.15 °C lower than that of the investigational room.

Ulpiani, G. [7] carried out a numerical and experimental study on the energy performance of nearly zero energy buildings with three different sunspace configurations (convective double-glazed, irradiative double-glazed, and irradiative single-glazed). The results showed that convective double-glazed has the best energy performance. Asdrubali et al. [13] used two stationary procedures (EN ISO 13790 and Method 5000) and a dynamic simulation tool (TRNSYS) to assess the effect of a sunspace on a building's energy balance. They concluded that the building energy demand was reduced by around 20% and all methods were in good agreement with actual energy-consumption data. Chiesa et al. [14] presented a study on the potential applicability of attached sunspaces in 50 locations (southern and central Europe) for heating seasons. They concluded that sunspace use in uninsulated or highly insulated buildings can reduce heating energy. The performance of sunspaces on adjacent rooms was not affected by increasing the internal mass capacity of the walls.

Babaee et al. [15] investigated the optimum design for passive heating of a sunspace in an apartment block in a cold climate (Tabriz) based on six main parameters (prevention of overheating by ventilation and shading; the dimension and form of the sunspace; common wall; glazing materials; sunspace orientation; and glazed surfaces). The results showed that the optimum sunspace design can reduce the adjacent room's heating energy by up to 46% compared to rooms without sunspaces. Bastien et al. [16] presented a methodology for sizing passive TES (thermal energy storage) systems in six different configurations of greenhouses. They concluded that the thermal mass on both the floor and the wall can increase the highest minimum operative temperature by up to 7 °C. Rempel et al. [17] investigated a series of field-proven sunspace models in the Pacific Northwest to quantify the limits of traditional thermal mass design in the area and to expose proper parameters concerning the ground configuration and size of floor-based thermal masses. They concluded that the thermal mass must be fully isolated from moist soils, the traditional rules greatly over-size thermal masses for the West Coast Marine climate, and the optimum mass design depends fundamentally on a space's thermal design priorities. They also [18] used the EnergyPlus software to investigate the energy performance of four Oregon sunspaces. Results showed that more than half of the total energy entering sunspaces originated as diffuse solar radiation and that 60–70% of the total was transmitted through shallow-pitched roof glazing.

Monge-Barrio et al. [19] studied the energy performance and optimum sunspace design for different climatic zones in Spain. The results showed that even in extreme conditions, the attached sunspaces had good thermal behavior in summer, as long as they were properly designed and used. Owrak et al. [20] used the EnergyPlus software to investigate the thermal performance of a room attached with a sunspace. They concluded that the sunspace along with the proposed heat storage system can reduce energy costs up to 87%. Ignjatović, D. [21] studied the energy performance of a typical residence attached with a sunspace. They concluded that the maximum impact on energy consumption reduction was realized by applying a sunspace with 30% ventilation openings and moderate quality glazing (shading coefficient of glazing is 0.5). Hilliaho, K. [22] used the IDA-ICE 4.6.1 software to study the impact of different types of glazed balconies on buildings' energy consumption in northern climatic conditions. The results showed that the energy saving in northern climatic conditions was greater than that in Central Europe.

Zhu et al. [23] carried out a numerical analysis on energy performance for new Yaodong dwellings attached with sunspaces by using the EnergyPlus software. The results showed that the convective heat transfer from the sunspace to the interior can reduce heating energy up to 28%. Sánchez-Ostiz et al. [24] carried out a numerical simulation and experimental study on the performance of an attached sunspace with vertical thermal storage and another with horizontal heat storage. They concluded that a sunspace with heat storage can improve the interior thermal performance of the adjacent room better than a simple sunspace or a window. Aelenei, D. [25] conducted a numerical study on the energetic performance of a residential building attached with different sunspace configurations in Portugal by using a dynamic simulation code. Results showed that the successful combinations for yearly energy consumption reduction have inner shading devices with high reflectance, natural ventilation of the sunspace, fully integrated sunspace configuration, and south orientation.

Tong et al. [26-28] assessed the natural ventilation potential by estimating the natural ventilation hour and used BES (building energy simulation) to calculate the energy-saving potential. The results provided policymakers and architects with valuable guidelines for the effective use of natural ventilation designs that meet local climatic conditions. Oliveti et al. [29] performed a numerical simulation study on the optical and heat efficiency of sunspaces by using the dynamic simulation tool called DEROB-LTH. They concluded that the heat capacity of the floor and wall has a significant impact on energy consumption. Bataineh, K.M. and N. Fayez [30] investigated the thermal energy performance of a living room attached to a sunspace in Amman-Jordan. They concluded that the heating energy consumption decreases by increasing the proportion of glazing surface to the opaque surface.

1.4.2. Trombe wall

Many scholars modified the traditional Trombe wall and found that the improved Trombe wall was more effective than the traditional Trombe wall.

Rabani, M. [31] carried out an experimental analysis on the heating performance of an improved Trombe wall, which can obtain solar irradiance from the directions of south, west, and east. The results showed that the improved Trombe wall can increase the maximum temperature of absorbers 10 °C higher than the traditional Trombe wall. Yu, B. [32] presented a study on the formaldehyde degradation performance and heating performance of a TC-Trombe wall combining the Trombe wall with the thermal catalytic technology. The results indicated that the TC-Trombe wall can save the formaldehyde degradation energy and space heating energy up to 33.1 kWh/m2 and 64.3 kWh/m2, respectively. The zigzag Trombe wall [33] was invented to reduce glare and unnecessary heat increase, which comprises the southeast part, the southwest part, and the south part. The southeast part and southwest part form an inward “V”-shaped wall. The south part and southwest part are traditional Trombe walls; the southeast part is a window.

Duan et al. [34] studied the thermal performances of two types of Trombe walls through a mathematical model, depending on the position of an absorber plate on the storage wall. They found that Trombe walls with absorber plates placed between the glass cover and the thermal storage wall are better than Trombe walls with the absorber plate pasted on the thermal storage wall. The particular exergy destruction, owing to absorption of the absorber plate is the largest and a higher absorber plate temperature is preferable in decreasing the total exergy destruction and increasing exergy efficiency. A non-ventilated Trombe wall with an additional window in the storage wall was proposed by Bellos, E. [35]. The results showed that the new non-ventilated Trombe wall can transfer the solar heat into the interior quickly, resulting in indoor temperature rising from noon to afternoon.

Leang, E. [36] used the Dymola/Modelica software to study the energy performance of a composite Trombe wall. They compared a M_PCM (mortar phase change materials) composite Trombe Michel wall with a concrete composite Trombe Michel wall. The results showed that the M_PCM composite Trombe Michel wall has a great heat recovered capacity, which can recover 50% more energy than the concrete composite Trombe Michel wall. Hu, Z. [37] carried out a study on the performance of three types of photovoltaic Trombe wall systems that can generate electricity and provide cooling/heating. Type 1 is photovoltaic blinds-integrated Trombe wall (PVBTW). Type 2 is photovoltaic cells attached to massive wall (PVMTW). Type 3 is photovoltaic cells attached to glass (PVGTW). The results showed that the type 1 (PVBTW system) can save 45% of the total electricity consumption and reduce the CO2 emission by 1.5 times compared with type 2 (PVMTW system) or type 3 (PVGTW system). Tunç, M. [38] conducted a numerical simulation study on the performance of the fluidized Trombe wall, in which the air cavity channel is fluidized by using low-density and highly absorbent particles. The results showed that fluidized Trombe walls gain more heat than traditional Trombe walls.

Adams, S. [39] presented an experimental analysis on the performance of the water Trombe wall with three different water storage wall thickness levels (3 inch, 6 inch and 9 inch). The results showed that the 9-inch and 6-inch water storage walls present better than the 3-inch water storage wall. The 3-inch storage wall did not adjust the temperature as well as the 9-inch and 6-inch water storage walls. The 9-inch and 6-inch water storage walls lagged a longer time than the 3-inch storage wall, which appeared to store and release the heat more efficiently. Sodha, M.S. [40] carried out a numerical study on the thermal performance of the solar transwall, which consists of a semi-transparent plate and glass walls. The results showed that the thermal performance of the solar transwall increases by increasing the water column thickness. Melero, S. [41] carried out an experimental study on the energy performance of a hybrid prototype Trombe wall integrated with a ceramic evaporative cooling system.

They concluded that the hybrid prototype Trombe wall can improve the comfort of interior in summer and winter. Taffesse, F. [42] developed a mathematical model of SPVT-TW (semitransparent photovoltaic thermal Trombe wall) for the heating of a room by using the MATLAB R2013a software. They concluded that 0.4 m is the optimal thickness of the SPVT-TW for thermal load leveling.

There are various components to help improve the efficiency of the Trombe wall such as insulation, fans, shading devices, vents, glazing type, the storage wall's materials and thicknesses, coating materials, and air cavity depth.

Ji, J. [43] proposed a numerical study on the thermal performance of the outer insulated Trombe wall. Results showed that the outer insulated Trombe wall performs more efficiently than the traditional Trombe wall, which can improve the operating efficiency of Trombe walls up to 56%. Ma, Q. [44] used the software of THERB for HAM to study the thermal energy efficiency of a double-layer Trombe wall assisted by a fan. Results revealed that the double-layer Trombe wall assisted by the fan can increase the double-layer Trombe wall efficiency close to 5.6% and reduce heating demand by 0.6 kWh/m3. Soussi et al. [45] studied the energy performance of the Trombe wall by using the TRNSYS software. Results showed that the total energy demand is reduced by using the movable solar overhangs, internal shading devices, and low-e Argon glazing.

Briga-Sá, A. [46] studied the energy performance of the non-ventilated and ventilated Trombe wall with various thickness in the storage wall. Results showed that for the non-ventilated Trombe wall, the heat gains increased with the decreasing of the thickness of the massive wall. However, for the ventilated Trombe wall, the heat gains decreased when the thickness decreased. Liu et al. [47] carried out a numerical and experimental analysis on the closing and opening the air vent of the Trombe wall. They concluded that it is best to close the vent one hour before sunset and open the vent two hours or three hours after sunrise. Mohamed, L. [48] conducted a numerical simulation and experimental study on the performance of the Trombe wall in Tunisia. Results showed that in the periods of the highest solar radiation, the room temperature reaches 25 °C for the single glazed Trombe wall but does not exceed 22 °C for the double glazed Trombe wall. The single glazed Trombe wall allows a good transmission of energy and improves the comfort level of the interior. However, Stazi et al. [49] concluded that the Trombe wall performance increased with the use of double glazing and low-e single glazing in term of global warming potential. Rabani et al. [50] studied the heating duration of a room with various materials of the Trombe wall in periods of non-sunny days. Results indicated that the heating duration of a room with the paraffin wax wall was 8 hours and 55 minutes, the salt wall was 8 hours 30 minutes, the brick wall was 8 hours 11 minutes, and the concrete wall was 7 hours 12 minutes.

Zhou, G. [51] performed an experimental analysis of the thermal behavior of a PCM (CaCl2·6H2O) storage wall. The results showed that the surface temperature of PCM (CaCl2·6H2O) performs speedy–slow changes during the 17.5-hour discharging process and rises speedy–slow–

speedy during the 6.5-hour charging process. Bojić, M. [52] studied the environmental and energy performance of Trombe walls that have various thickness of the storage wall. Results showed that for natural gas heating, the optimal thickness of clay bricks is around 0.25 m. For the electrical heating, the optimal thickness of clay bricks is around 0.35 m. Nwosu, N.P. [53] conducted an analysis of the heat transmission balance of a Trombe wall. The results showed that the highly absorptive coating materials can improve the storage capacity of the Trombe wall. Burek, S.A.M. [54] conducted an experimental study on the mass flow rate and heat transfer in the Trombe wall. The results showed that the mass flow rate increases by increasing the heat input and air cavity depth. If the heat input is as high as 1000 W/m2, the air cavity depth has no effect on the Trombe wall's efficiency.

1.4.3. Double skin facade

Barbosa et al. [55] reviewed the studies on the energy and thermal performance of buildings with DSF (double skin facade). They concluded that the 'site' parameters (wind speed and direction, solar irradiance, orientation), the 'Façade design' parameters (cavity openings and depth, double skin facade structure, the properties of outer skin glazing, shading device), and the 'building' parameters (number of floors/the cavity height, openings and wall-to-window ratio, inner skin materials) affect the efficiency of DSF (double skin facade).

Souza et al. [56] carried out an experimental and numerical study on the performance of a naturally ventilated DSF (double skin façade). The results showed that DSF (double skin facade) can help to reduce the indoor heat gain and help to reduce wall temperature. Hudişteanu et al. [57] studied the effect of wind on the cooling effect of integrated photovoltaic plates and the ventilation of double skin facade cavity (DSF). The results showed that the decrease in the temperature of the photovoltaic panel leads to the increase of efficiency and power generation by 11%.

Koo et al. [58] studied the performance of a building with double skin facade. The results showed that the average temperature of the ventilated air cavity is 0.6 K lower than the average temperature of the unventilated air cavity. Li et al. [59] analyzed the heat transfer in an integrated PCM (phase change material) blind system and DSF (double skin facade). The results showed that the phase change material blind system can help to stabilize the outlet airflow of the double skin facade while improving the convective heat transfer in the double skin facade between the blind surface and the air cavity. Su et al. [60] investigated the thermal performance of double skin façade for different climate regions in China. They concluded that the major factors affecting double skin façade thermal performance are various for the various climate regions. For Harbin, Shanghai, and Beijing, the optional factors for double skin facade are: grill = 60°; width of opening = 0.1 m; distance between outer glass and blind = 0.7 m; and width of cavity = 0.8 m. For Guangzhou, the optional factors for double skin facade are: grill = 60°; width of opening = 0.1 m; distance between outer glass and blind = 0.1 m; and width of cavity = 0.2 m.

Luo et al. [61] proposed an experiment and simulation study on the thermal performance of a double skin facade with photovoltaic blinds (PVB-DSF). The results showed that PVB-DSF can save 25.57% and 12.16% of energy in summer compared with traditional double skin facade without and with shading blinds. Ding et al. [62] carried out an experiment and numerical study on the natural ventilation performance of the building with solar chimney. They concluded that the ventilation rate was increased by increasing the height of the solar chimney. Chou et al. [63] investigated the effectiveness of DSF (double skin façade) in reducing solar heat gain. The results showed that a building with DSF (double skin façade) having WWR (wall-to-window ratio) of 0.3 can reduce ETTV (envelope thermal transfer value) by 45%. Yılmaz et al. [64] compared the heat loss of a double skin facade and a single skin façade office buildings to show the effect of double skin facade on building energy requirement in Istanbul. They concluded that various properties of the materials, various transparency proportion, and various glazing types will give various results. Gratia et al. [65] analyzed the effect of the cavity opening on the evolution of the average temperature of the cavity. They concluded that the average temperature of the cavity decreases with the increase of openings, and there is no linear relationship with the size of the openings.

Aksamija et al. [66] investigated energy performance of three types of double skin facade (multistory, corridor and box window) in different climate types. The results showed that the difference in energy consumption between three types of double skin facade is small. Chan et al. [67] carried out an experimental and numerical study on the energy performance of double skin façade with various glazing types. The results showed that, compared with a single skin facade, a double skin façade system with the inner clear glazing and outer double reflective glazing and can save about 26% of the building cooling energy each year. Jiru et al. [68] conducted a numerical study on heat transfer and airflow for a double skin façade system equipped with a venetian blind. The results show that, compared with blind angles ($\theta = 90°, 45°, 0°$), the position of the blinds (inner, middle and outer) have a greater effect on the distribution of velocity, temperature, and surface heat transfer coefficients. Radhi et al. [69] carried out a numerical study on the thermal performance of double skin façade. They concluded that the optimal cavity size is between 0.7 and 1.2 meters.

1.5. Research objectives and purposes

Based on the author's review, the characteristics of the sunspace, DSF and Trombe wall are summarized, and various components that can help to improve the efficiency of Trombe walls. However, there is no study on the utilization of heat in air layer in external wall of a house with a central air conditioning and air circulation system. To reduce the heating load, during the heating period, the heat from the air channel is sent to the central air conditioning room, from where it is then distributed and stored throughout the house by way of air circulation.

In this thesis, we conducted an actual survey to understand the situation of heat utilization of the air channel and used numerical simulations to examine the effective method of heat utilization of the air channel. The experimental work introduced here mainly focuses on the analysis of the performance of the sunspace, when the air is sent to the central air conditioning room from the air channel of the sunspace. The sunspace is located on the south side of the house with a central air conditioning and air circulation system. The house in Miyazaki, Japan. We ran numerical simulations using THERB for HAM software to investigate effective methods of using the heat from inside the air channel (sunspace, DSF and Trombe wall), as well as possible structural improvements. We also conducted the energy performance comparison between a sunspace, double skin facade and Trombe wall.

1.6. Organization of Thesis

This thesis has eight chapters. Figure 1.5 is the structural of the thesis.

1.6.1. Chapter 1. Introduction

In the chapter, background, previous research, objectives, purposes, and configuration of the thesis are described.

1.6.2. Chapter 2. Method

In the chapter, an overview of the demonstration house and simulation conditions.

1.6.3. Chapter 3. Performance of sunspace under different operation methods

In the chapter, we conducted an actual survey to understand the situation of heat utilization of the sunspace and used numerical simulations to examine the effective method of heat utilization of the sunspace.

1.6.4. Chapter 4. Experimental analysis of thermal performance

In the chapter, we conducted an actual survey of the thermal environment for demonstration houses in Miyazaki city and analyzed the thermal environment of each room.

1.6.5. Chapter 5. Effect of sending heat from the sunspace to the adjacent room

In the chapter, the main purposes of this chapter are to identify heat collection effects and heating load reduction effects of a sunspace structure based on numerical simulation by examining efficient heat utilization methods within a sunspace and floor plans in winter.

1.6.6. Chapter 6. Performance comparison between a sunspace, double skin facade and Trombe wall

In the chapter, numerical studies on the energy performance of the sunspace, DSF (double skin facade) and Trombe wall were carried out.

1.6.7. Chapter 7. Numerical analysis of the thermal environment

In the chapter 7, we clarified the thermal environment of each room during heat utilization of the sunspace, double skin facade and Trombe wall and examined whether it is possible to maintain thermal environment suitable for daily behavior.

1.6.8. Chapter 8. Conclusions

In the chapter 8, the results of the thesis are summary zed.

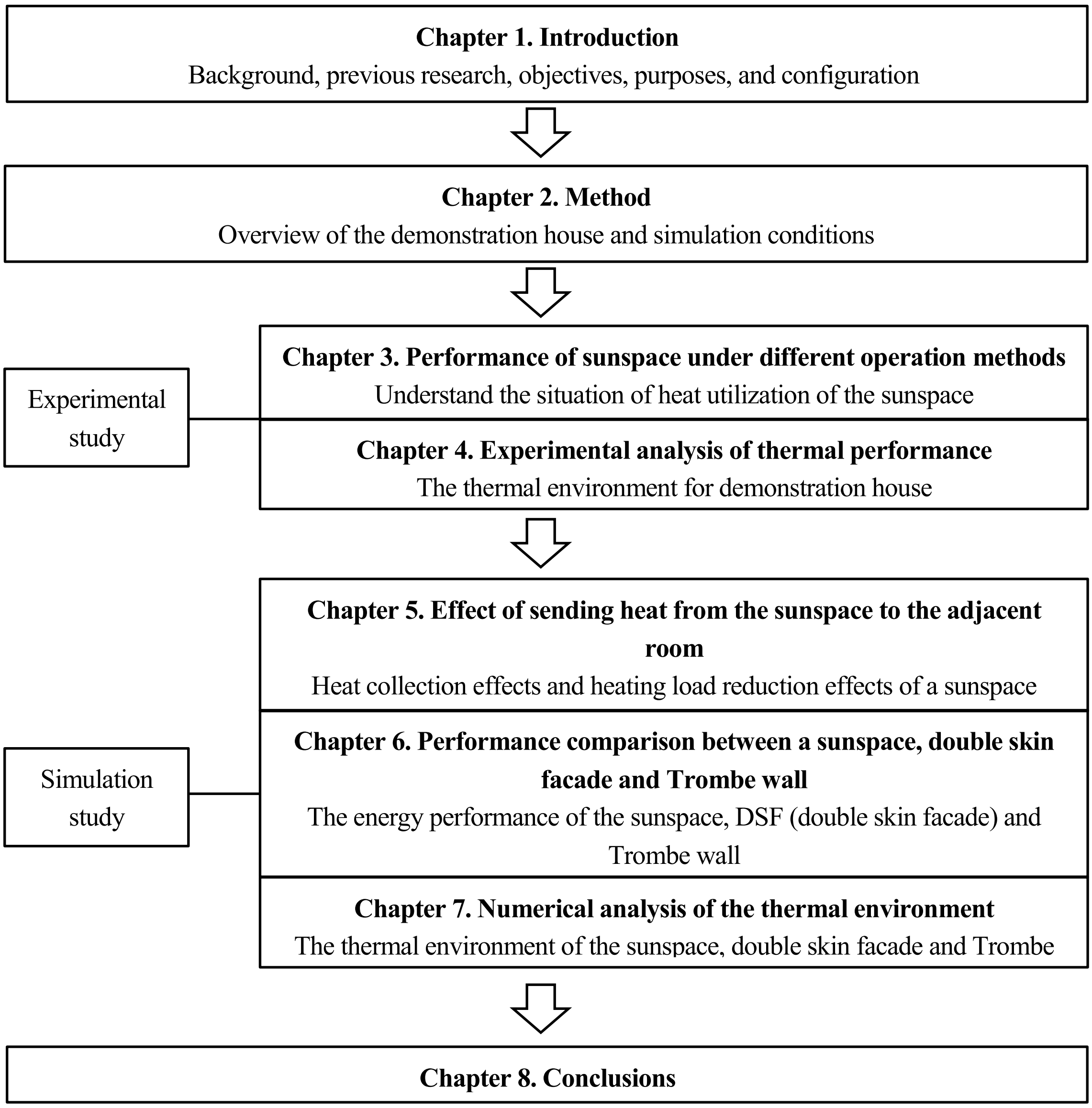

Figure 1.5 The structural of the thesis

Chapter 2.

Method

2. Method

2.1. The house description

The demonstration house is a two-story wooden house located in Miyazaki city, Miyazaki prefecture. Figures 2.1 (a) and (b) show the house's outer appearance and the inside of the attached sunspace. The direct gain method and the attached sunspace method were applied. The heat collected in the attached sunspace was sent to the central heating, ventilation, and air conditioning system (HVAC) machine room to reduce the heating load. Table 2.1 shows the house's specifications. Tables 2.2 to 2.12 show the construction details of the house.

Figure 2.1 The demonstration house: (a) The outer appearance; (b) The inside of the attached sunspace

The annual insolation area classification is used to distinguish the potential of solar power generation. The annual insolation area is divided into five classification in Japan. A4 means an area where the annual insolation is high. Winter insolation area classification is a solar radiation area classification in the heating period (a period when average daily temperature is less than 15 degrees). The winter insolation area is divided into five classification in Japan. H3 means that a region has a moderate amount of solar radiation. Area classification of energy saving standard is determined by the Heating Degree Day (HDD). 7 region means that the Heating Degree Day (D_{18-18}) is more than 500 and less than 1500.

Table 2.1 Specifications for the house

Location		Miyazaki, Japan
Annual insolation area classification		A4
Area classification of energy saving standard		7 region
Winter insolation area classification		H3
Total floor space		115.5 [m^2]
Total building skin space		350.9 [m^2]
Direct gain opening space		8.1 [m^2]
Sunspace opening space		9 [m^2]
Window glass	Sunspace (outside)	Pair glass
	Other	Triple ShannonIIS
Skin heat transmission coefficient average (UA)		0.26 [W/m^2・K]
Air conditioner room		Air conditioning of heat pump unit , DC motor, Central HVAC system
Ventilating equipment		Total enthalpy heat exchanger

Table 2.2 Constructions with their layers used in ground

Layer	Thickness (m)	λ (W/m K)	ρ (kg/m^3)	cp (J/kg K)
Concrete	0.27	1.2	2200	840
Rigid polystyrene foam	0.1	0.035	32	1470

Table 2.3 Constructions with their layers used in foundation wall

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Concrete	0.185	1.2	2200	840
Rigid polystyrene foam	0.1	0.035	32	1470

Table 2.4 Constructions with their layers used in exterior wall

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Siding board	0.04	0.59	1100	840
Air cavity	0.018	0.022	1.2	1000
Moisture-prevention sheet				
Polystyrene foam	0.05	0.028	28	1130
Structural plywood	0.009	0.111	550	1880
Air cavity	0.018	0.022	1.2	1000
Rigid polystyrene foam	0.08	0.035	32	1470
Moisture-prevention sheet				
Gypsum board	0.012	0.22	700	870

Table 2.5 Constructions with their layers used in interior wall

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Gypsum board	0.012	0.22	700	870
Air cavity	0.05	0.022	1.2	1000
Gypsum board	0.012	0.22	700	870

Table 2.6 Constructions with their layers used in floor and ceiling

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Structural plywood	0.015	0.111	550	5880
Air cavity	0.05	0.022	1.2	1000
Structural plywood	0.024	0.111	550	1880
Solid floor	0.015	0.111	550	5880

Table 2.7 Constructions with their layers used in roof

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Concrete	0.15	1.2	2200	840
Asphalt roofing	0.025	0.03	40	1470
Siding board	0.06	0.514	1100	840
Rigid polystyrene foam	0.2	0.035	32	1470

Table 2.8 Constructions with their layers used in interior wall (sunspace)

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Gypsum board	0.012	0.22	700	870
Polystyrene foam	0.05	0.028	28	1130
Rigid polystyrene foam	0.08	0.035	32	1470
Gypsum board	0.012	0.22	700	870

Table 2.9 Constructions with their layers used in floor and ceiling (sunspace and air conditioning room)

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Structural plywood	0.015	0.111	550	5880
Rigid polystyrene foam	0.08	0.035	32	1470
Air cavity	0.05	0.022	1.2	1000
Structural plywood	0.024	0.111	550	1880
Solid floor	0.015	0.111	550	5880

Table 2.10 Constructions with their layers used in outer window (sunspace)

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m^3)	cp (J/kg K)
Glass	0.003	0.78	2540	770
Air cavity	0.12	0.022	1.2	1000
low-e				
Glass	0.003	0.78	2540	770

Table 2.11 Constructions with their layers used in inner window (sunspace)

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m³)	cp (J/kg K)
Glass	0.003	0.78	2540	770
Air cavity	0.12	0.022	1.2	1000
Glass	0.003	0.78	2540	770
Air cavity	0.12	0.022	1.2	1000
Glass	0.003	0.78	2540	770

Table 2.12 Constructions with their layers used in other windows

Layer	Thickness (m)	λ (W/m K)	ρ (kg/ m³)	cp (J/kg K)
Glass	0.003	0.78	2540	770
low-e				
Air cavity	0.12	0.022	1.2	1000
Glass	0.003	0.78	2540	770
Air cavity	0.12	0.022	1.2	1000
low-e				
Glass	0.003	0.78	2540	770

2.2. Central air conditioning and circulation system

Figure 2.2 shows the central air conditioning and circulation system in winter. External air is sent to the central HVAC room through air filters and a total heat exchanger. The air in the central HVAC room is then sent to each room after its temperature and humidity are adjusted by a residential heat pump air-conditioning unit. The air in the rooms returns to the central HVAC room through vent layers in the wall and duct. Part of the air is discharged to the outside by a total heat exchanger. The rest of the air is sent back to the rooms after going through the central HVAC room again. For this reason, 24-hour mechanical ventilation is performed through fans. The ventilation of the fan is 150 m^3/h, 250 m^3/h during strong operation, and the maximum is 280 m^3/h. To reduce the heating load, during the heating period, the heat from the air channel of the sunspace is sent to the central HVAC room, from where it is then distributed and stored throughout the building by way of air circulation. Further, during the cooling period, the cooling load can be reduced by opening the windows on the outside of the sunspace and using the roof and wing walls to provide shade from the sun.

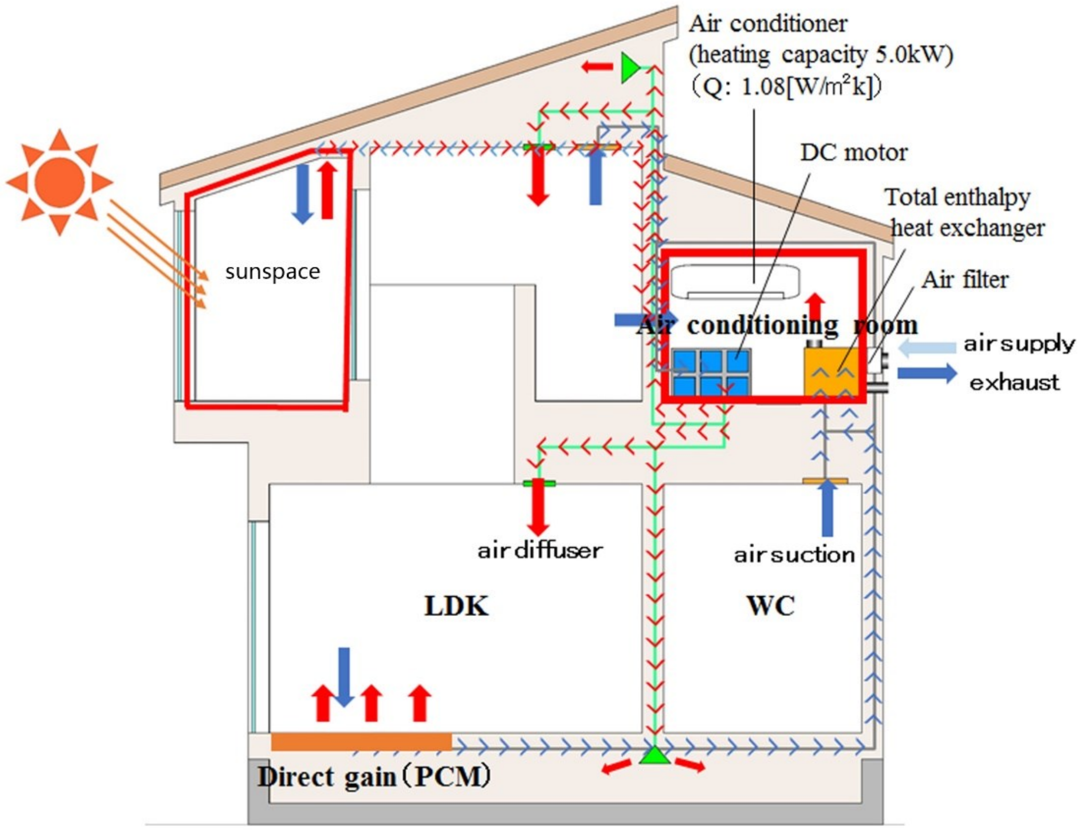

Figure 2.2 The central air conditioning and circulation system in winter

2.3. Measured equipment

For the measurement, the RTR-503 device was used to measure the temperature and humidity of the sunspace and the room. The sensors were located in the sunspace center and the room center. The Vantage Pro2 Console device was used to measure the solar radiation, wind direction, wind speed, temperature, and humidity outdoors. Table 2.13 shows the accuracy and range of all measurement devices.

Table 2. 13 Uncertainties of measurement devices

Device	Measuring parameter	Range	Accuracy
RTR-503	Temperature	0-55°C	±0.3°C
	Humidity	10~95%	±5% RH
Vantage Pro2 Console	Solar radiation	0 to 1800W/m^2	±5% of full scale
	Wind direction	0 to 360°	±3°
	Wind speed	0 to 809m/s	±1m/s
	Temperature	-40° to +65°C	±0.5°C
	Humidity	1 to 100%	±3% RH

2.4. THERB for HAM

This study used THERB for HAM software to investigate effective methods of using heat from inside the sunspace. Figure 2.3 shows the composite movement of heat, humidity and air in the house. THERB for HAM (Simulation Software of the Hygrothermal Environment of Residential Buildings for Heat, Air, and Moisture) is a dynamic calculation software that can calculate the temperature, humidity, heating, and cooling loads of multi-zone buildings [70]. Akihito Ozaki developed the THERB for HAM software initially. The calculation result of THERB for HAM was validated throughout the building energy simulation test (BESTEST) in Japan. The features of THERB for HAM are as follows [71]:

- Combined calculation of heat and moisture transfer and airflow
- Prediction of the hygrothermal environment (temperature, humidity, predicted mean vote, standard effective temperature)
- Temperature and humidity control or predicted mean vote control
- Considering the time variation of convective heat and moisture transfer
- The forced and natural heat and moisture transfer coefficient are calculated for each part based on the dimensionless equation
- Strict geometric calculation of sunlit and shading areas of outside and inside
- Multi-layer window model
- Multiple reflections of transmitted solar radiation through windows
- Nonlinearity of radiation heat transfer
- Mutual radiation between inside surfaces
- Network airflow model

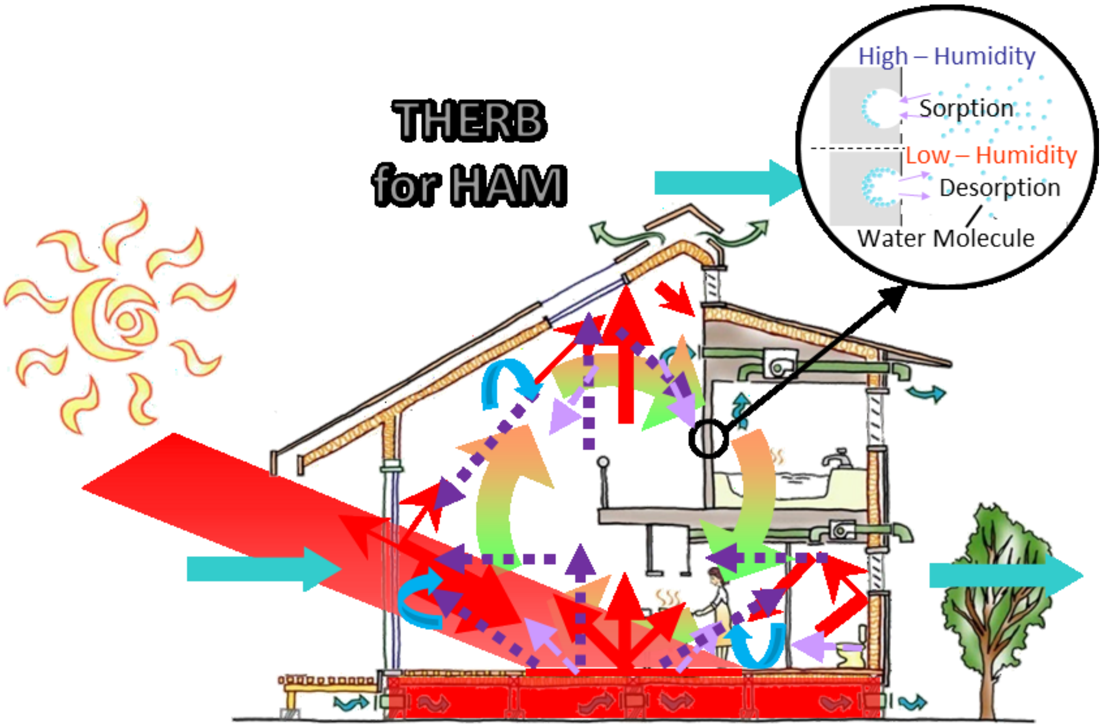

Figure 2.3 The composite movement of heat, humidity and air in the house

2.4.1. Conductive Heat Transfer

The finite difference method is applied to the model of one-dimensional transient thermal conduction of multi-layer walls. Regarding thermal conduction to the ground, the finite difference method of two or three dimensions is applied to the previous calculation of the ground temperature and then the results are used as the input excitation for conductive calculation of the earthen floor and basement walls.

2.4.2. Convective heat transfer

Table 2.14 shows the convective heat transfer coefficient. By default, the convective heat transfer coefficients are recalculated at every time step on all surfaces of the exterior, interior and cavities of buildings using dimensionless equations which are derived from either the profile method for boundary layer (based on the energy equation, the momentum equation and the fluid friction) or defined from the experimental findings according to natural or forced convection. Furthermore the natural convective heat transfer coefficients are classified into either vertical or horizontal surfaces. It is possible to use the functional equations of the wind direction and velocity for the exterior convective heat transfer coefficients and the functional equations of the temperature difference between surface and room for the interior convective heat transfer coefficients. It is also possible to set constant heat transfer coefficients all day long or modify the coefficients to take into consideration air-conditioning time for every part of the building.

Table 2.14 Convective Heat Transfer Coefficient [70]

Part of Buildings	Dimensionless Number
Exterior	$Nu = 0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}$
Interior (Vertical Plane)	$Nu = 0.241(Gr_i \cdot \mathrm{Pr})^{0.4}$ $Gr_i = g\beta\Delta T_a l^3 / \upsilon^2$
Interior (Horizontal Plane)	$Nu = C \cdot Ra_f^m$ $Ra_f = Gr_i \cdot \mathrm{Pr}$ $f = (T_s + T_\infty)/2$
Upward	C=0.58, m=1/5
Downward	C=0.54, m=1/4 (Ra_f: 2E4 to 8E6) C=0.15, m=1/3 (Ra_f: 8E6 to 1E11)
Cavity (ventilated)	$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$
Cavity (closed)	$Nu = 0.035(Gr_c \cdot \mathrm{Pr})^{0.38}$ $Gr_c = g\Delta T_s l^3 / T_m \upsilon^2$

Gr: Grashof number, Nu: Nusselt number, Pr: Prandtle number, Ra: Rayleigh number, Re: Reynolds number, Tm: mean temperature of surfaces, Δ Ta: temperature difference between surface and air, Δ Ts: temperature difference between surfaces, g: gravitational constant, l: length, β: expansion coefficient, υ: kinematic viscosity

2.4.3. Radiant heat transfer

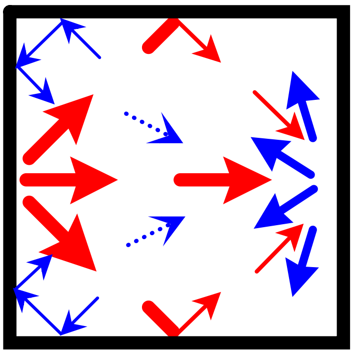

Figure 2.4 Multiple reflection of long-wave radiation [70]

Figure 2.4 shows the multiple reflection of long-wave radiation. On the exterior surfaces of the buildings, the standard method of using the radiant heat transfer coefficients and atmospheric radiation is applied. On the interior of buildings, instead of the general method (that is, the calculation of heat transfer between surface and indoor air and radiation between surfaces), the use of the long-wave absorption coefficient makes it possible to simulate a net absorption of radiant heat as a consequence of multiplex reflection among interior surfaces. Mutual radiation between the surfaces of cavities in walls and windows can also be calculated.

2.4.4. Incident solar radiation

Incident solar radiation on the exterior and into the interior of buildings is divided into direct and diffuse solar radiation and calculated for all parts of the building in all directions using accurate geometric calculations of shaded and unshaded portions of the building by considering the influence of overhangs and wings. Isotropic model or anisotropic models can be chosen for diffuse solar radiation. Transmitted solar radiation is calculated by the multilayer window model and considers multiplex reflection (depending on an incidence angle of solar radiation) between not only the glazing layers but also between the window and interior shade at every time step. The multiplex reflection of both direct and diffuse solar radiation among interior surfaces including re-transmission of solar radiation from the inside to the outside through the windows is calculated by using the short-wave absorption coefficient. In addition the absorption coefficients of long and short wave are applied to radiant heat emitted from lights and appliances, etc.

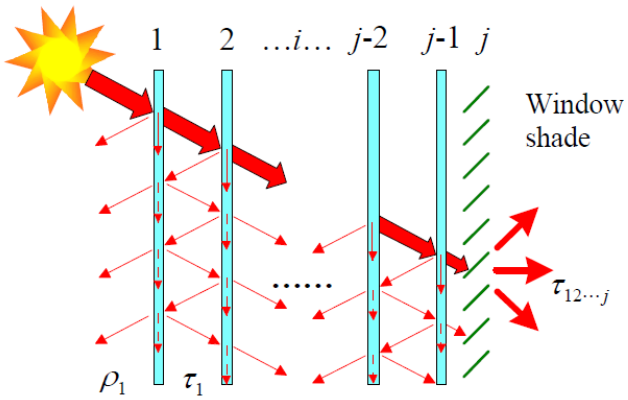

Figure 2.5 Multi-layer window model [70]

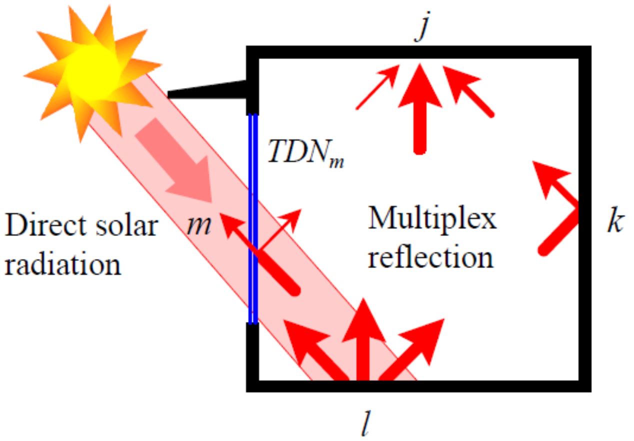

Figure 2.6 Multiplex reflection of transmitted direct solar radiation [70]

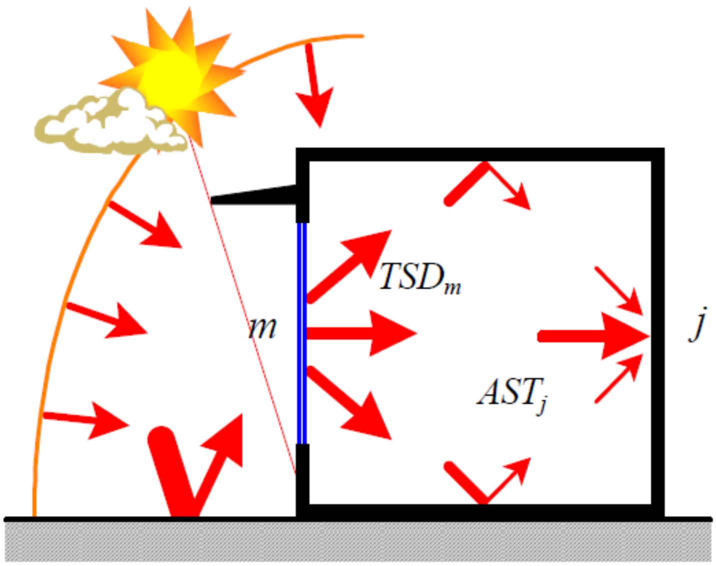

Figure 2.7 Multiplex reflection of transmitted sky diffuse solar radiation [70]

2.4.5. Ventilation

The network airflow model integrating a thermal model with a plant model estimates natural and forced ventilation quantities of each zone (rooms and cavities) caused by air leakage, infiltration and mechanical ventilation. As for independent ventilated cavities in the walls, it is possible to estimate airflow quantities by hydrodynamic analysis as the solution to the equations of motion, energy and continuity. Constant ventilation quantities can be also set every hour for all zones.

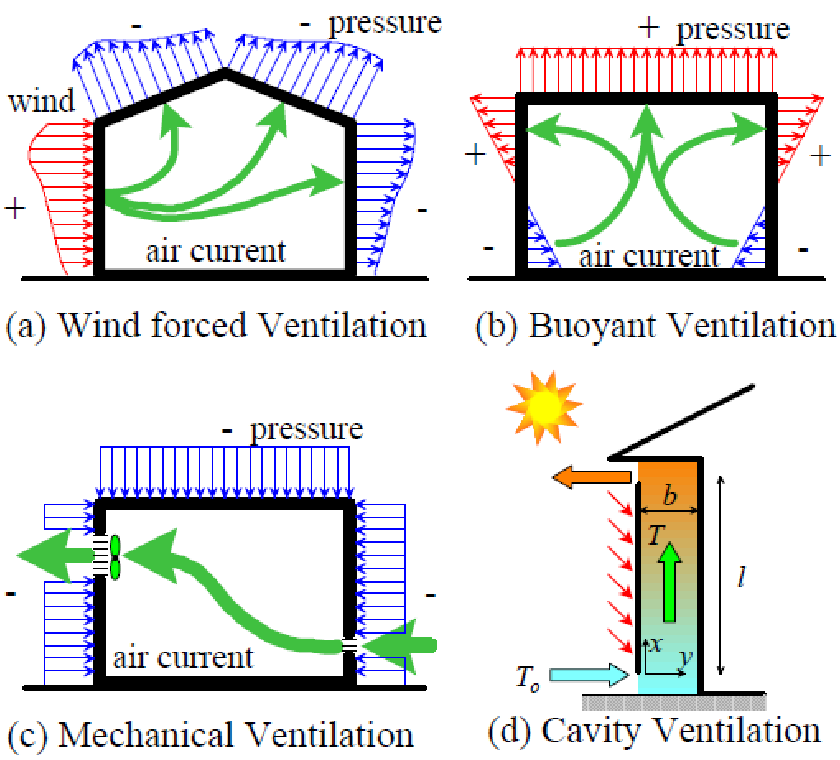

Figure 2.8 Mechanical or natural ventilation [70]

2.4.6. Conductive Moisture Transfer

Water Potential which is derived by applying the chemical potential of thermodynamics to moisture diffusion is used as the driving force of moisture transfer. This approach is proposed to be more accurate than other models based on physical properties such as vapour pressure. The model called P-model using water potential makes it possible to combine moisture transfer with heat transfer perfectly, and take into account internal energy and external forces such as gravity.

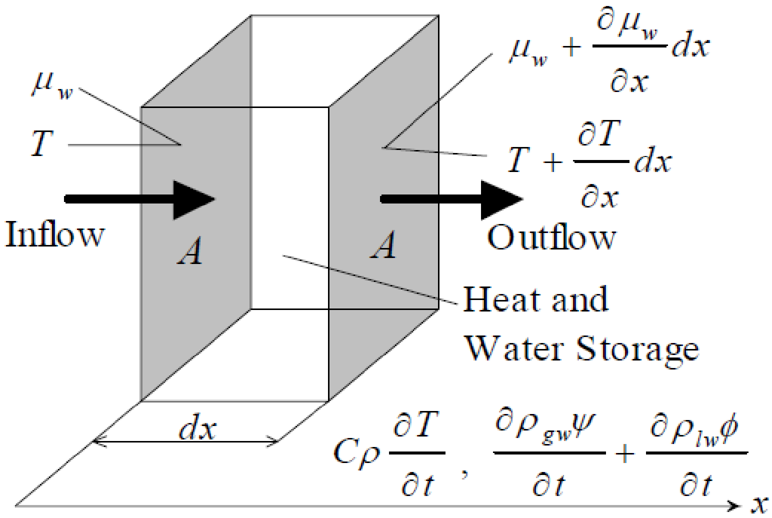

Figure 2.9 Conductive heat and moisture transfer [70]

2.4.7. Convective moisture transfer

The convective moisture transfer coefficients on all surfaces of the exterior, interior and cavities of buildings are calculated from the dimensionless Sherwood number, which is derived on the basis of the analogy between heat and mass transfer. The Sherwood number can be calculated by replacing the Prandtle number with Schmidt number shown in Table 2.14.

2.3.8. Control of space conditioning

Control methods for space conditioning are classified into three types: heating, cooling, and simultaneous heating and cooling. By default, humidity control and temperature control are linked. Temperature and humidity set-point and ranges can be optionally set every hour. Moreover the control of humidity is automatically performed in the case when the sensible temperature such as PMV is set as the set-point of air-conditioning.

2.4.9. Flow Chart

Figure 2.10 shows the flow chart of THERB for HAM. One of the characteristics of THERB for HAM is that calculation nodes are automatically numbered for each room component or element and associated both temperature and humidity calculation.

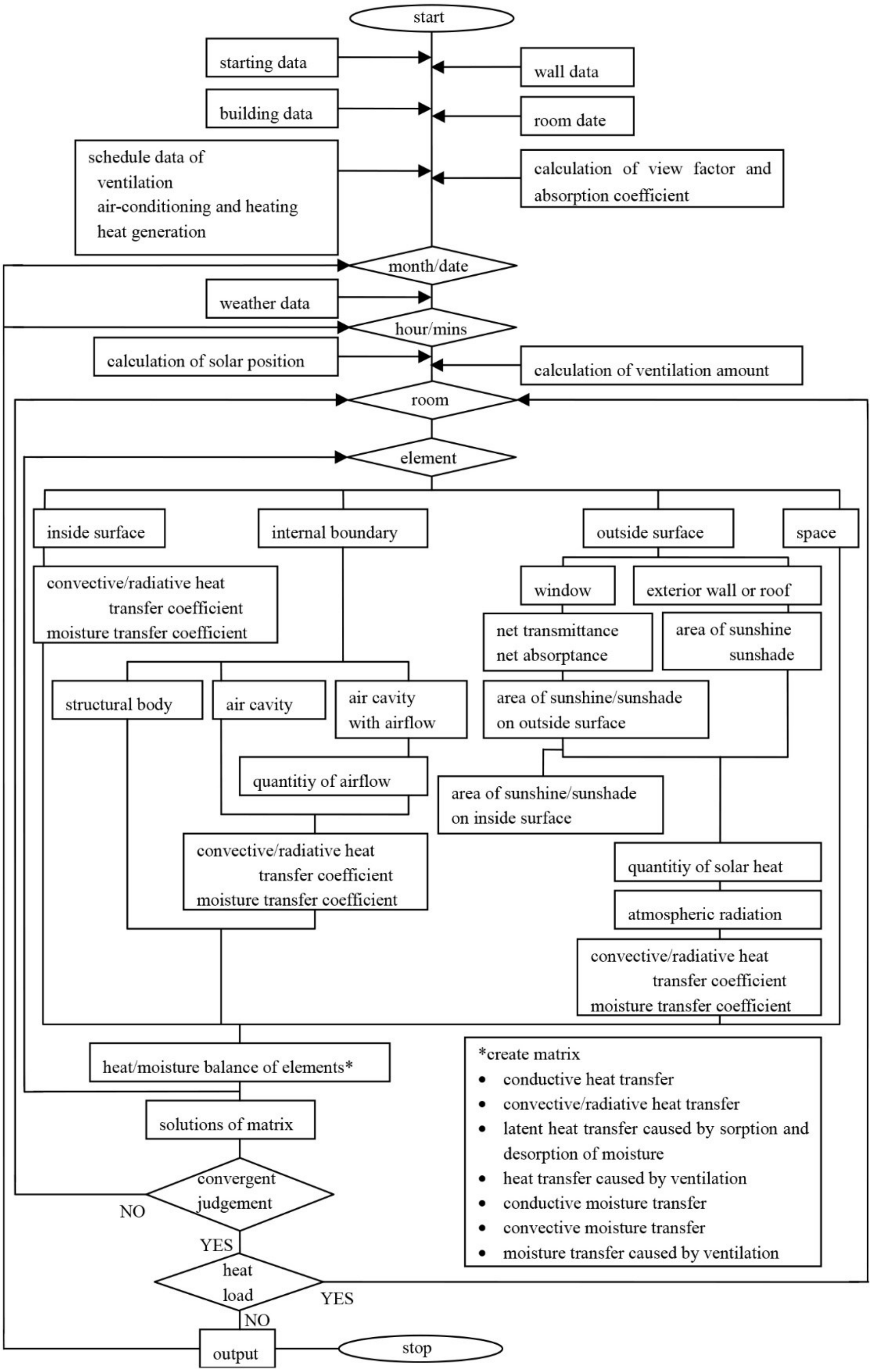

Figure 2.10 Flow chart of THERB for HAM [70]

2.5. Plan reconstruction

Figures 2.11 to 2.17 are floor plans of Model Io (a balcony on the second floor), Model I (a sunspace on the second floor [the experimental house]), Model II (the sunspace on the first and second floors), Model III (double skin facade on the second floor), Model IV (double skin facade on the first and second floors), Model V (Trombe wall on the second floor), and Model VI (Trombe wall on the first and second floors), respectively.

For Models I to VI, during the cooling period, the cooling load can be reduced by opening the windows on the outside of the air layer and using the roof and wing walls to provide shade from the sun. For Models I and III, the window on the interior side of air layer can be opened to the bed room. For Models II and IV, the window on the interior side of air layer can be opened to the bed room and LDK.

It was assumed the air layer on the second floor of Models II, IV and VI was made of perforated metal and the air moved between the air layer of the first and second floors. The air inside the air layer on the second floor is sent to the air conditioning room, and the air in the air conditioning room is sent to the air layer on the first floor.

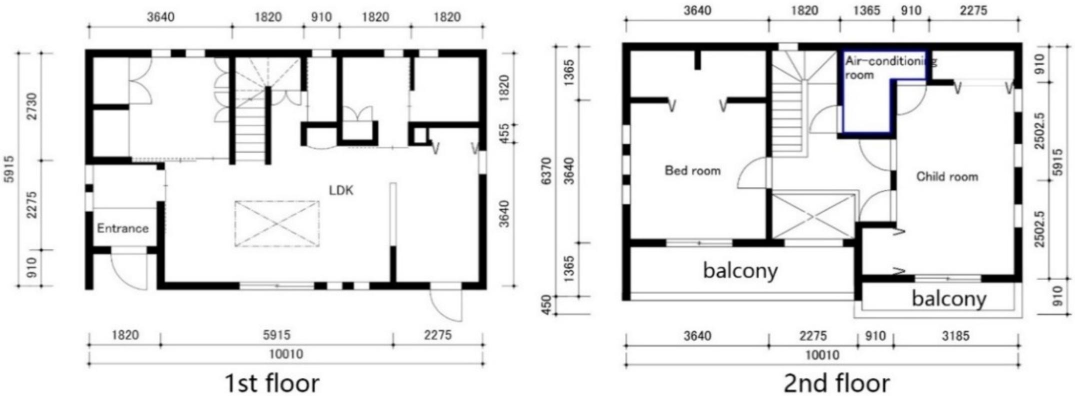

Figure 2.11 Model Io floor plans

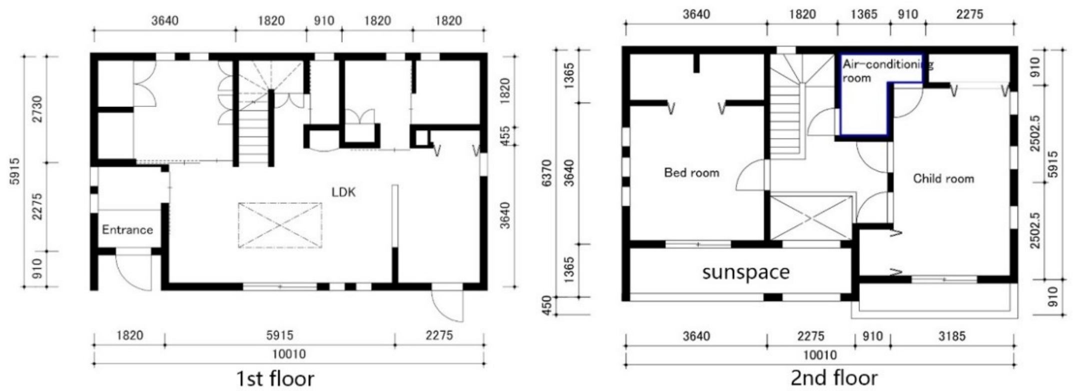

Figure 2.12 Model I floor plans

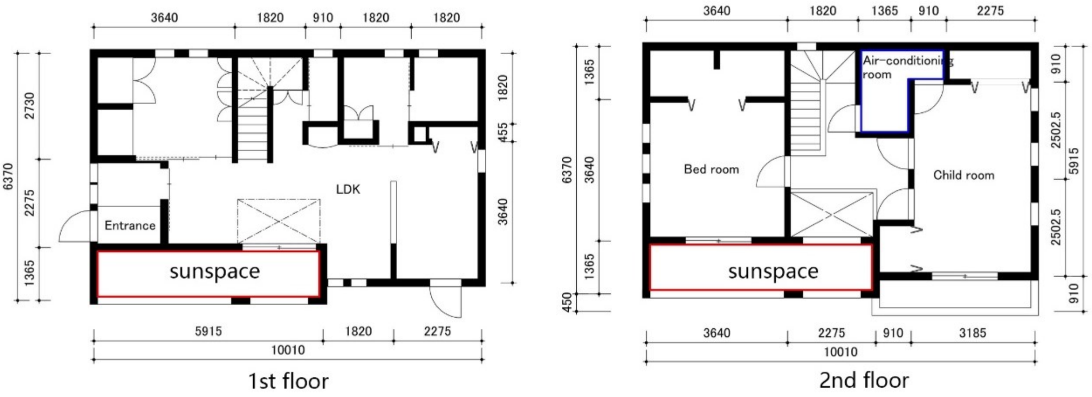

Figure 2.13 Model II floor plans

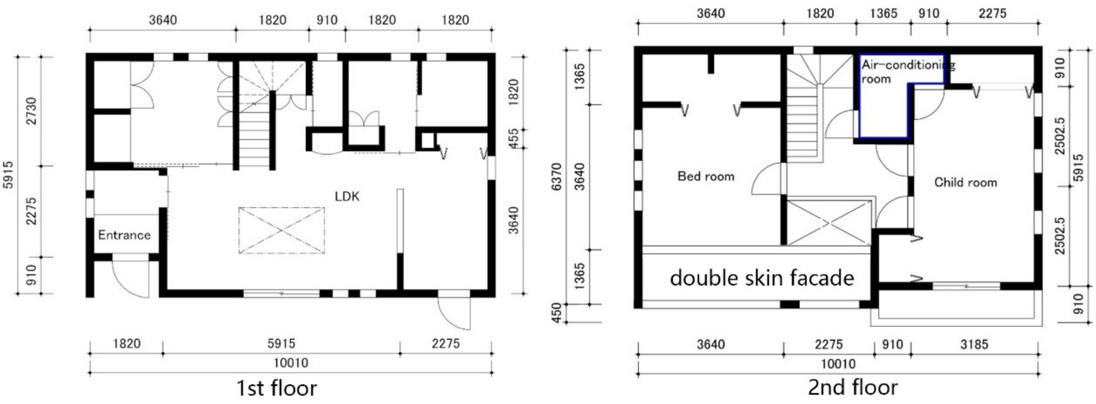

Figure 2.14 Model III floor plans

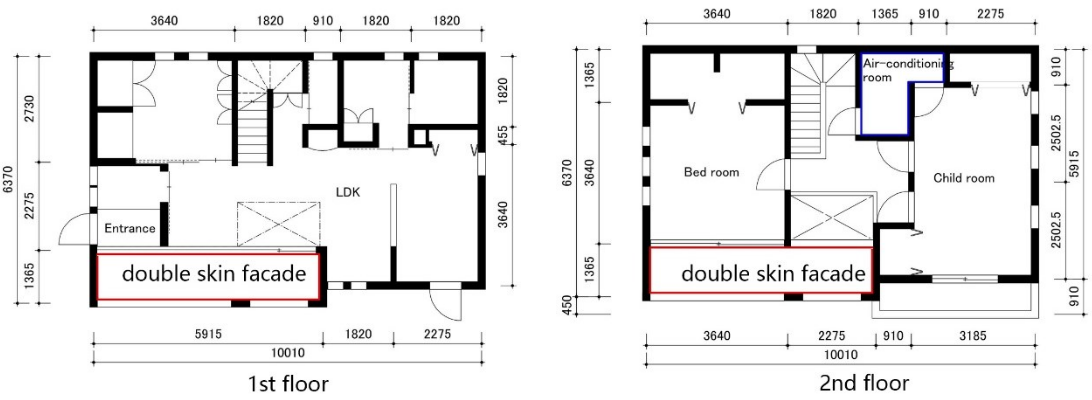

Figure 2.15 Model IV floor plans

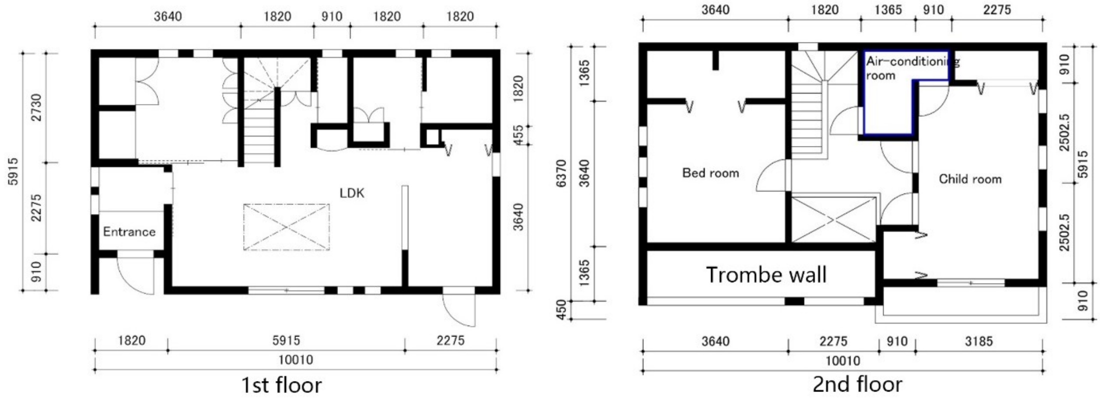

Figure 2.16 Model V floor plans

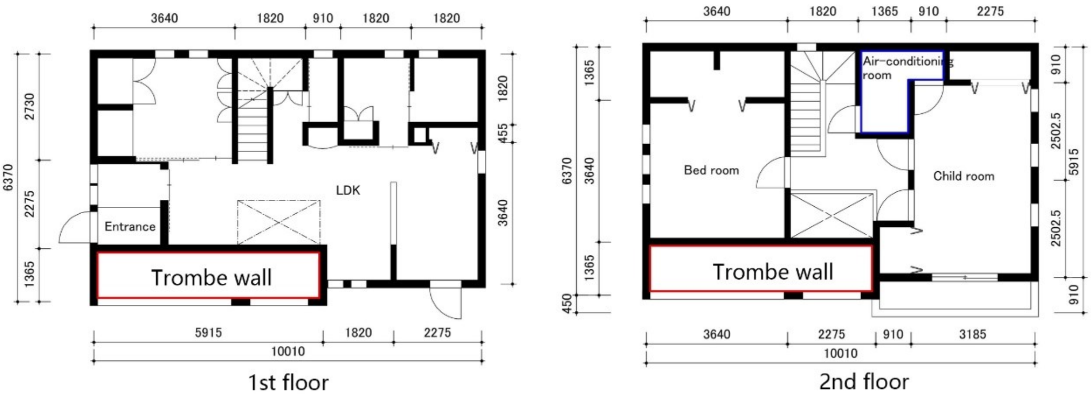

Figure 2.17 Model VI floor plans

2.6. Occupancy and air conditioning schedule

Figure 2.18 shows the time schedule of father (worker), child (primary school), and mother (housewife/worker) at home. Figures 2.19 and 2.20 show the heat and humidity generation schedule for model I (housewife). Figures 2.21 and 2.22 show the heat and humidity generation schedule for model I (worker). Figures 2.23 and 2.24 show the heat and humidity generation schedule for model II (housewife). Figures 2.25 and 2.26 show the heat and humidity generation schedule for model II (worker). The heat and moisture generation schedule is generated based on the schedule software, which is developed by SHASE (the society of heating, air-conditioning and sanitary engineers of Japan). The washroom ventilation switch is turned on only when the washroom is used.

There are three ways to use central air conditioning: all-day air conditioning, intermittent air conditioning, and intermittent individual room air conditioning. The all-day air conditioning: The central air conditioning system is on for 24 hours, and air is sent to each room from the central air conditioning room. Intermittent air conditioning: The central air conditioning is on only when people are at home, and air is sent to each room from the central air conditioning room. In the absence of people, the central air conditioning is off and the air circulation only needs to meet the necessary ventilation (0.5 times/h). Intermittent individual room air conditioning: The central air conditioning is on only when people are at home, and air is sent to the room where people live from the central air conditioning room. Only the necessary amount of ventilation (0.5 times/h) is sent to the room where no one lives.

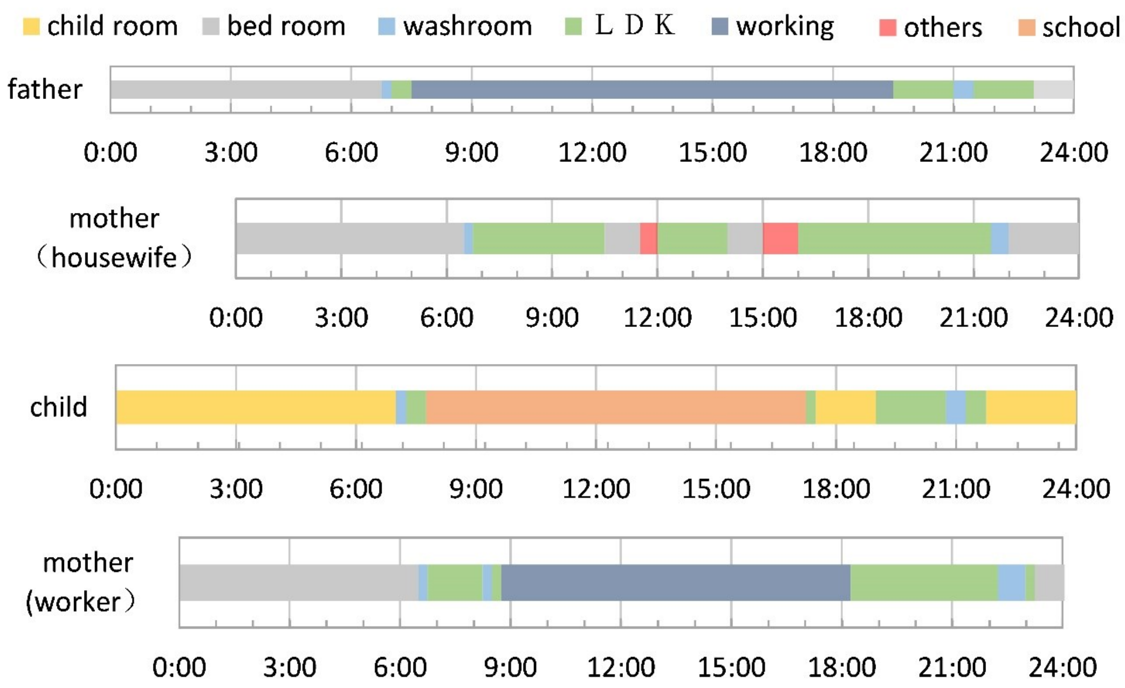

Figure 2.18 Time schedule

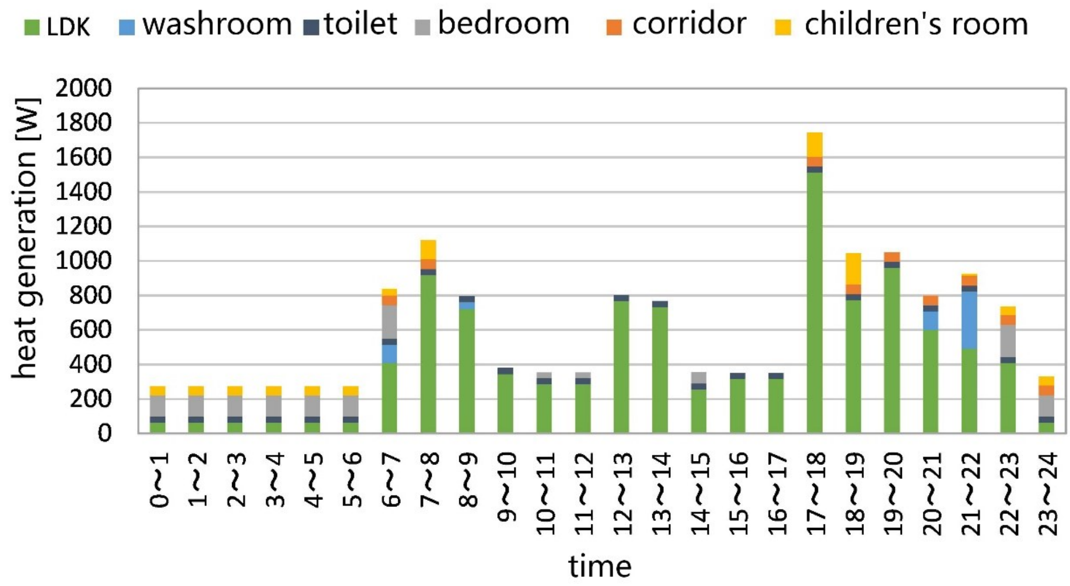

Figure 2.19 Heat generation schedule for model I (housewife)

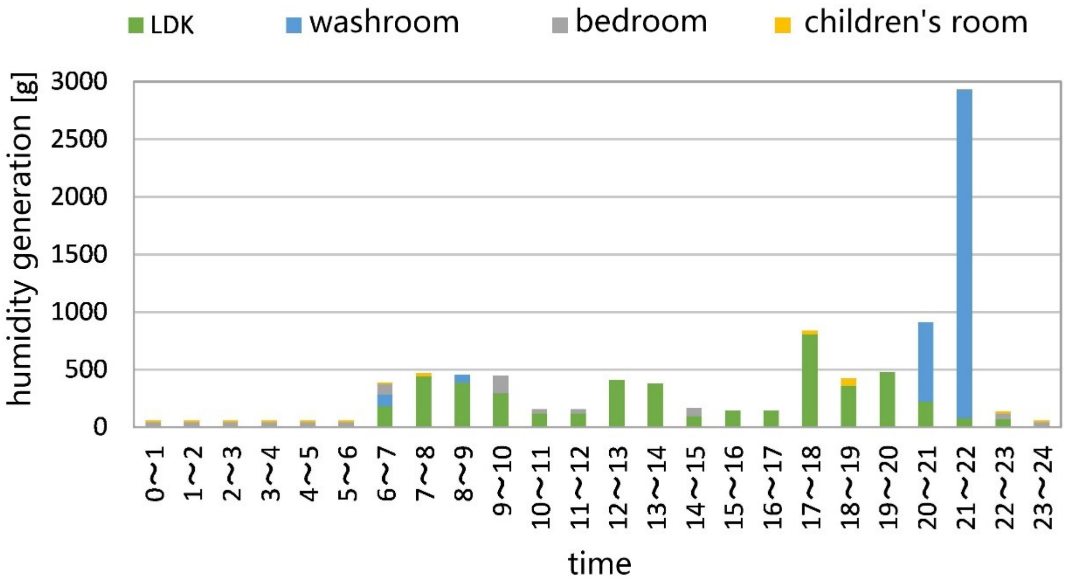

Figure 2.20 Moisture generation schedule for model I (housewife)

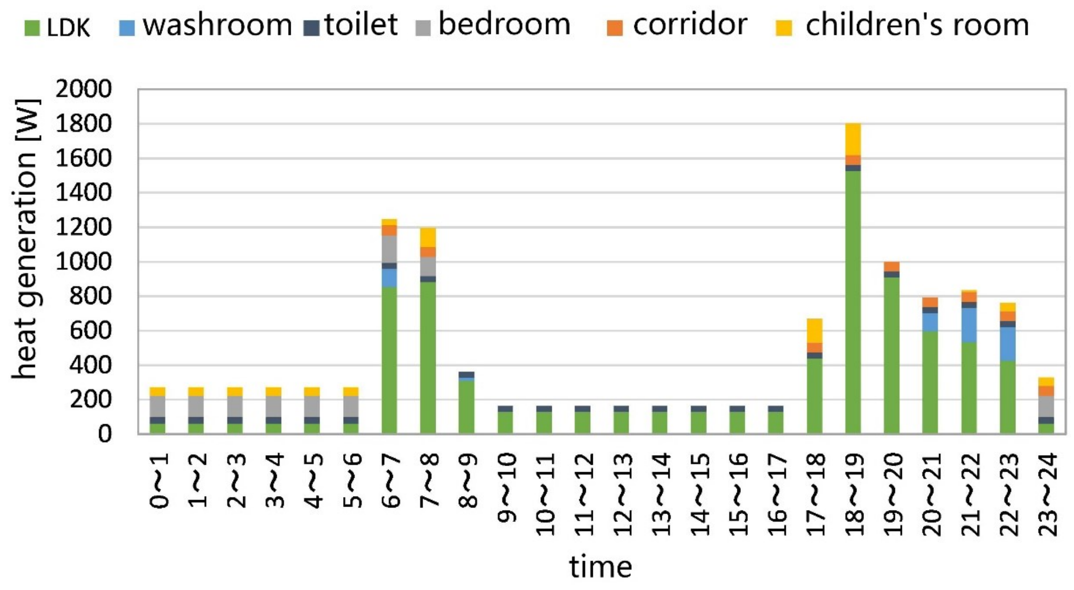

Figure 2.21 Heat generation schedule for model I (worker)

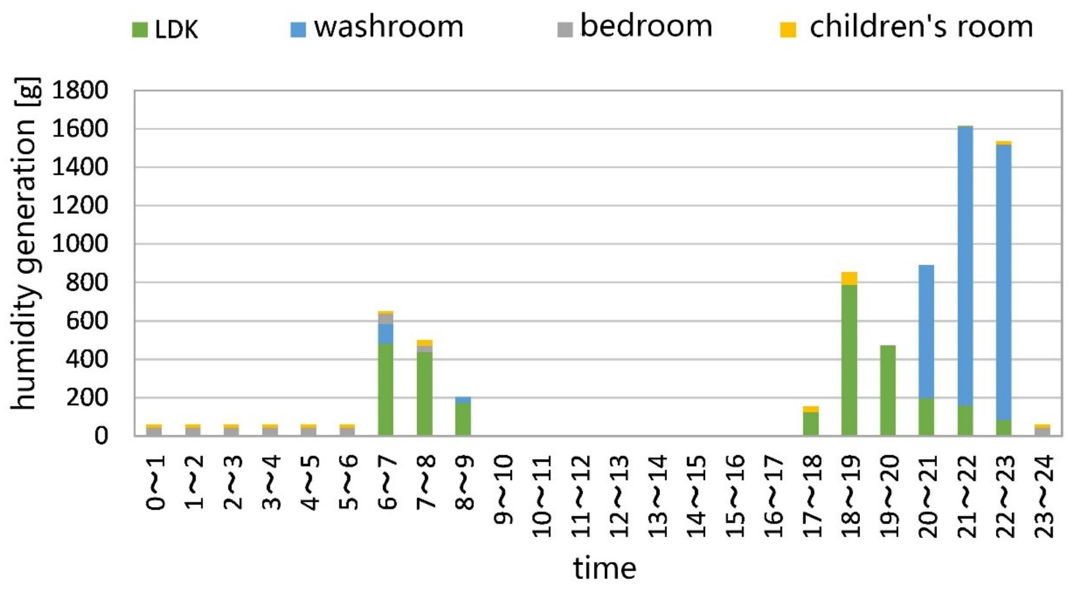

Figure 2.22 Moisture generation schedule for model I (worker)

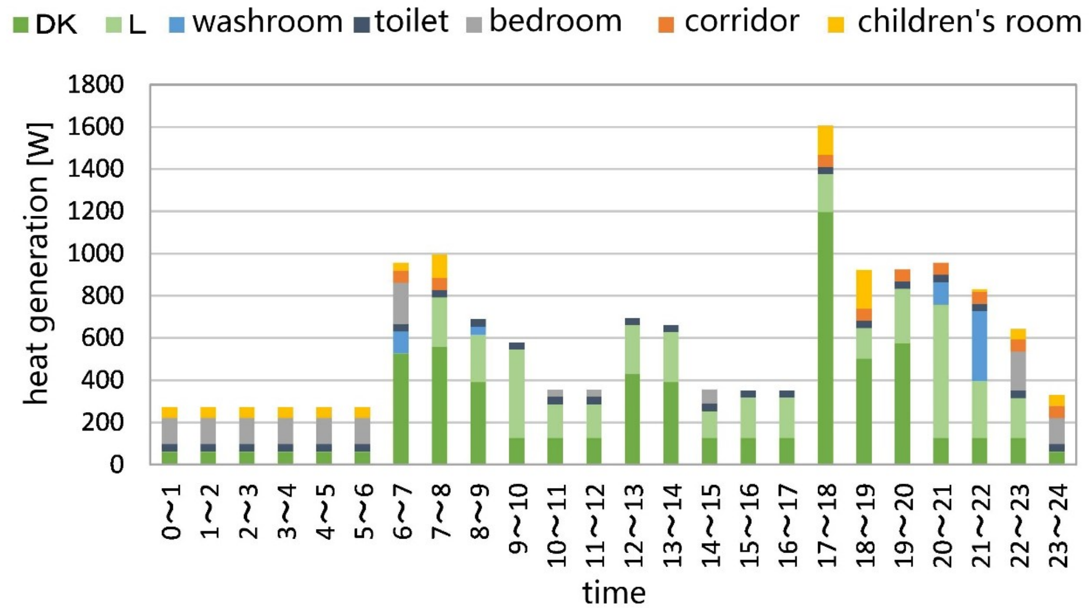

Figure 2.23 Heat generation schedule for model II (housewife)

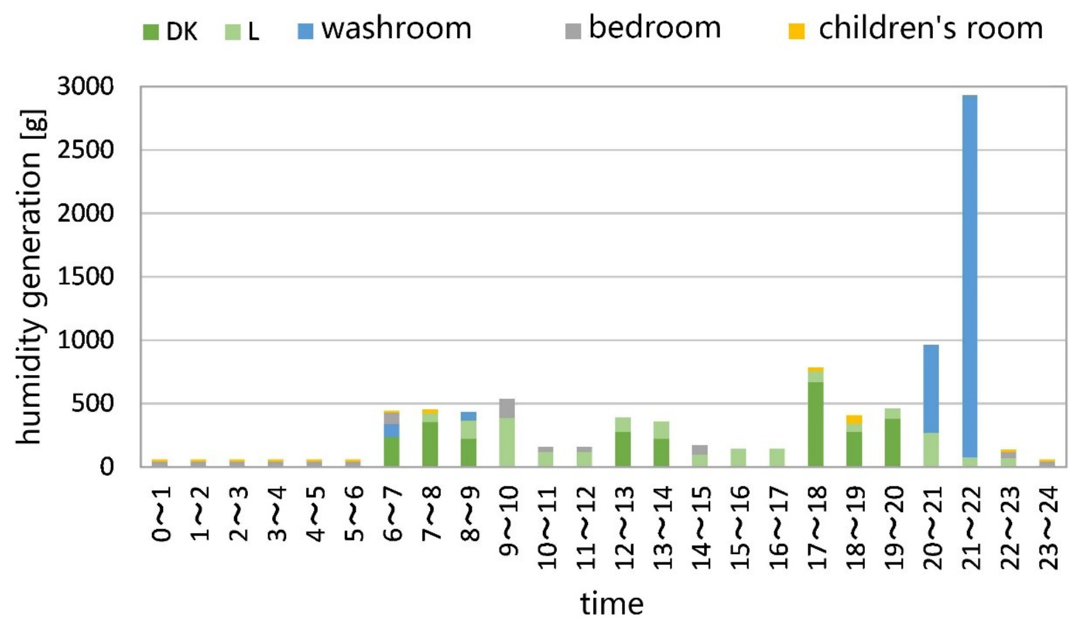

Figure 2.24 Moisture generation schedule for model II (housewife)

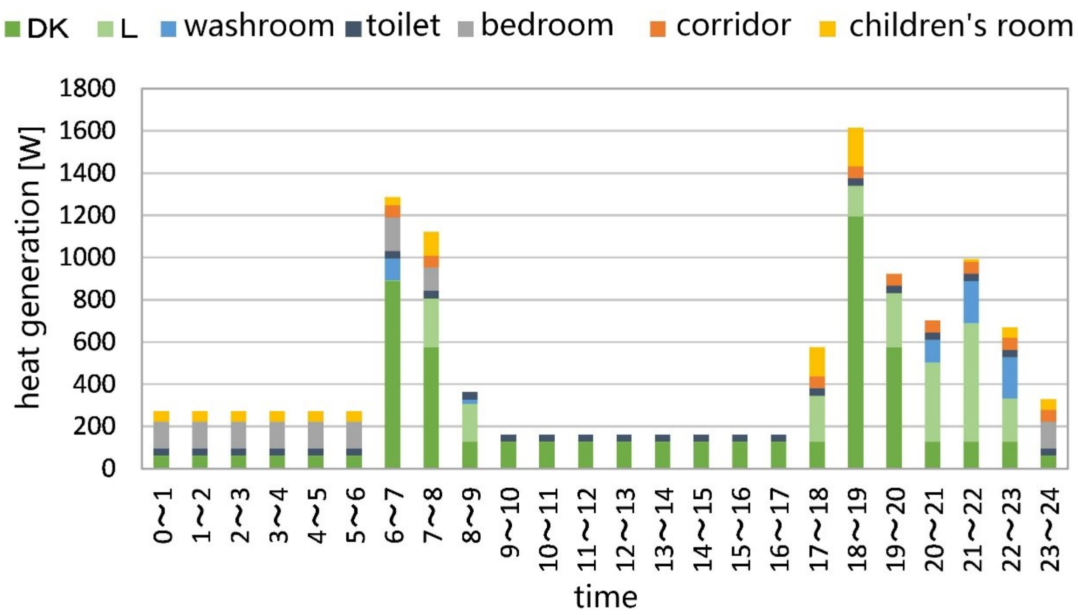

Figure 2.25 Heat generation schedule for model II (worker)

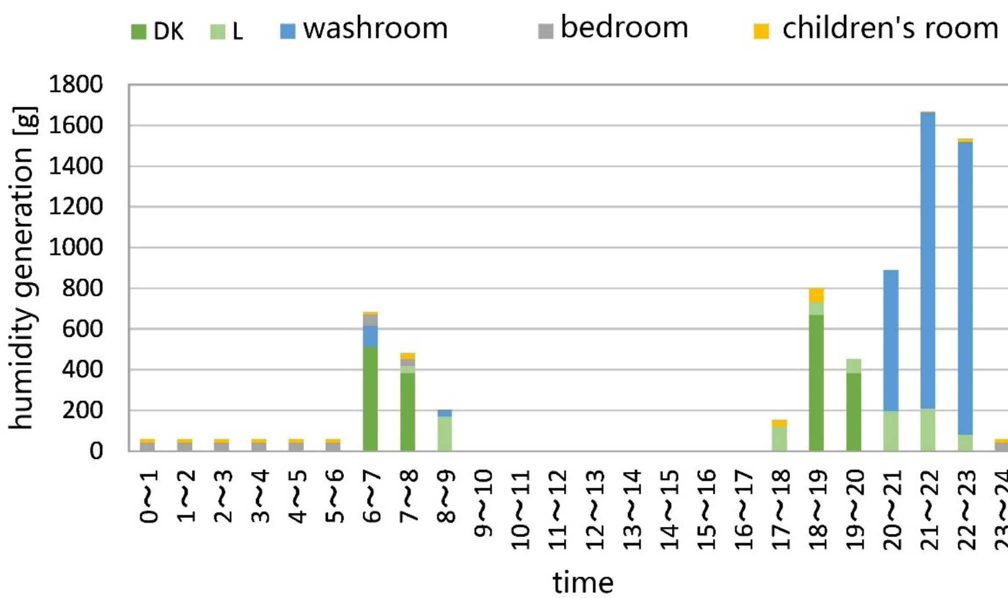

Figure 2.26 Moisture generation schedule for model II (worker)

2.7. Schedule software

Schedule software is a program that can generate life schedule for housing energy calculations. Schedule Ver. 2 used in this paper was based on data from the survey of 67898 people in Japan in 1990.

Tables 2.15 and 2.16 show the heat generated by body and equipment, respectively. Tables 2.17, 2.18 and 2.19 show the moisture generated by body, equipment and gas combustion, respectively. We developed heat and moisture generation schedule with reference to these values.

Table 2.15 The heat generated by body (room temperature: 26 ^{o}C)

Status	Sensible heat (W)	Latent heat (W)	Moisture (g/h)
Sit down	65	43	70
Sedentary (office)	65	77	117
Stand up (without walk)	65	60	90
Moderate work (employees)	65	109	164
Metalworker (sitting)	80	170	256
Sawn timber (heavy work)	172	352	530

Table 2.16 The heat generated by equipment

Equipment	sensible heat (W)	Latent heat (W)	Moisture (g/h)
Incandescent	Watts	0	0
Oven and toaster	Watts * 0.8	Watts * 0.2	0.3
Hair dryer	668	116	175
Gas stove	65 (W/m^2)	109 (W/m^2)	780 (W/m^2)

Table 2.17 The moisture generated by body

Status	Room temperature			
	10	20	25	35
Sit down	32	39	65	151
Light exercise	52	125	175	298
Normal exercise	73	182	290	358
Heavy exercise	162	311	373	442

Table 2.18 The moisture generated by equipment

Name	Summary	Moisture (g/h)
Pan (diameter: 22 cm)	Vigorously boiling without a lid	1400-1500
	General, with cover	500-700
Kettle	Vigorously boiling without a lid	1300-1400
	General, with cover	50
Bathtub	People: 2, area: 0.5 ^{2}m	500-1000
Bathhouse	Area: 1 ^{2}m	500-1000
Bathing person		1000-1500

Table 2.19 The moisture generated by gas combustion

Type	Amount	Heat (KJ)	Moisture (g)	Summary
City Gas	1 ^{2}m	13960	450-550	Coal gas
City Gas	1 ^{2}m	13730	600	Pure methane gas
City Gas	1 ^{2}m	13960	500	Petroleum propane gas
Household propane	588 g (1 ^{2}m)	12930	950	Pure propane
Kerosene	320 g	14080	450	

Chapter 3.

Performance of sunspace under different operation methods

3. Performance of sunspace under different operation methods

3.1. Introduction

In this chapter, we conducted an actual survey to understand the situation of heat utilization of the sunspace and used numerical simulations to examine the effective method of heat utilization of the sunspace. In the measurement, the RTR-503 device is used to measure the temperature and humidity in the sunspace air channel and the room space. The sensors are located in the sunspace air channel center and the room center. The Vantage Pro2 Console device is used to measure the solar radiation, wind direction, wind speed, temperature, and humidity outdoors. The experimental work introduced here mainly focuses on the analysis of the performance of the sunspace, when the air is sent to the air-conditioned room from the air channel of the sunspace. We ran a numerical simulation using THERB for HAM software to investigate effective methods of using the heat from inside the sunspace, as well as possible structural improvements.

3.2. Calculation details and conditions

Table 3.1 gives the air conditioning schedule for each method of air conditioning and Table 3.2 gives an overview of the numerical simulation cases. As the table shows, we developed nine cases with different combinations of air conditioning methods, amounts of airflow from the sunspace to the air conditioning room, presence or absence of a thermal storage medium, and open or closed windows. "c" shows that a thermal storage medium (concrete) was installed as the foundation of the floor inside the sunspace. The concrete thickness was 100 mm. The concrete has a length of 4.1 m and width of 0.91 m. The thermal conductivity of the concrete was 1.6 W/m K. The concrete specific weight was 2300 kg/m^3. The specific heat of concrete was 880 J/kg K. "w" shows that the window in the second-floor bedroom bordering the sunspace was left open. We also assumed that air was only sent from the sunspace to the central air conditioning room between 12:00 and 18:00. The simulated work presented here mainly focuses on the analysis of the performance of the sunspace under the following three different air conditioning methods.

(1) In the condition of using the air conditioning all day, we compared the effect of the amounts of airflow on the heating load reduction (case I, case II and case III). We also compared the effect of the thermal storage medium on the heating load reduction (case II and case IIc).

(2) In the absence of air conditioning, we investigated whether it was possible to keep the Living/dining/kitchen area at a comfortable temperature by only using the airflow from inside the sunspace (case V, case VI and case VIc). We also investigated the effectiveness of keeping the window open in the second floor bedroom bordering the sunspace and letting the heat from the sunspace circulate into that room (VIc, VIcw and VIcw 24 hr.).

(3) In the condition of using intermittent air conditioning, we studied the effect of the airflow on the living room/dining room/kitchen temperature (case IV).

Table 3.1 The air conditioning schedule

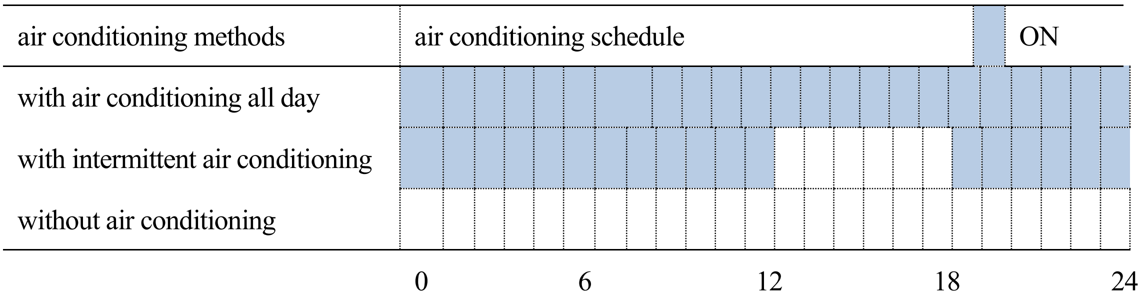

Table 3.2 Overview of the numerical simulation cases

case	skin heat transmission coefficient average ［W/m^2・h］	air conditioning methods	amounts of airflow from the sunspace to the air conditioning room（12:00～18:00）
I	0.26（a suitable demonstration house）	with air conditioning all day	0 m^3/h
II			500 m^3/h（the state of demonstration house）
IIc			500 m^3/h＋thermal storage medium（concrete）
III			1000 m^3/h
IV		with intermittent air conditioning	500 m^3/h（the state of demonstration house）
V		without air conditioning	0 m^3/h
VI			500 m^3/h（the state of demonstration house）
VIc			500 m^3/h＋thermal storage medium（concrete）
VIcw			500 m^3/h＋thermal storage medium（concrete）＋window opening

3.3. Measurement results

Figure 3.1 shows the temperature of the air in the sunspace within two months. The highest daily temperature of the air in the sunspace was higher in February than in March, and in early February there were days when the temperature rose to 40 °C or more. It seems that even in early February, the coldest outside temperatures, sending air from the channel of the sunspace to the central HVAC room was an effective way of reducing the heating load. However, the fact that the maximum daily air channel temperature of the sunspace dropped to 20 °C or less on days with little solar radiation indicates that air inside the sunspace cannot be sent to the central HVAC room every day.

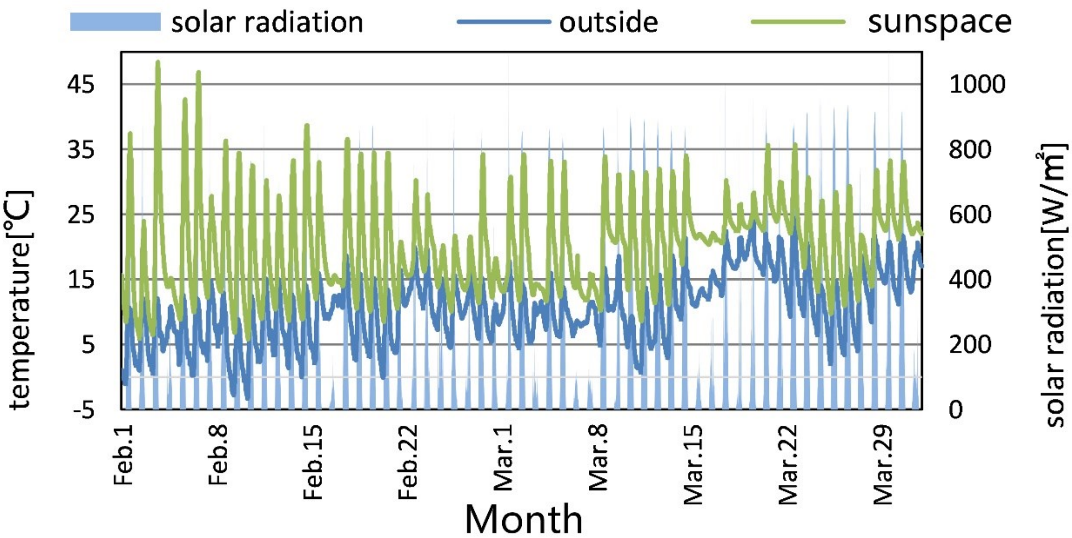

Figure 3.1 Air temperature in the sunspace within two months

Figure 3.2 shows the variation in the temperature of each room when air is being sent from the channel of the sunspace (without air conditioning). The heat collected from the sunspace is sent to the central HVAC room from 12:00 to 18:00 and then distributed to each room. Airflow from inside the sunspace resulted in an approximate 1°C temperature rise in the central HVAC room. In Japan, the minimum air exchange per hour is 0.5. The volume of the sunspace air channel is 12.9 m^3. The ventilation from the sunspace into the central HVAC room is 500 m^3/h. The sunspace temperature growth rate decreased after the beginning of airflow at 12:00. The sunspace temperature reduction rate decreased after the end of airflow at 18:00. The temperature of the sunspace is affected by the outdoor air temperature and solar radiation. The outdoor air temperature is not changed so much from 13:00 to 16:00 and the sunspace has a significant delay effect on the air temperature fluctuations. As a result, even if the amount of solar radiation decreases, the temperature of the sunspace continues to increase. However, the temperature rises a little in the living/dining/kitchen area and the temperature inside the sunspace remained high even after airflow to the central HVAC room commenced and this air could potentially be used to provide further heat.

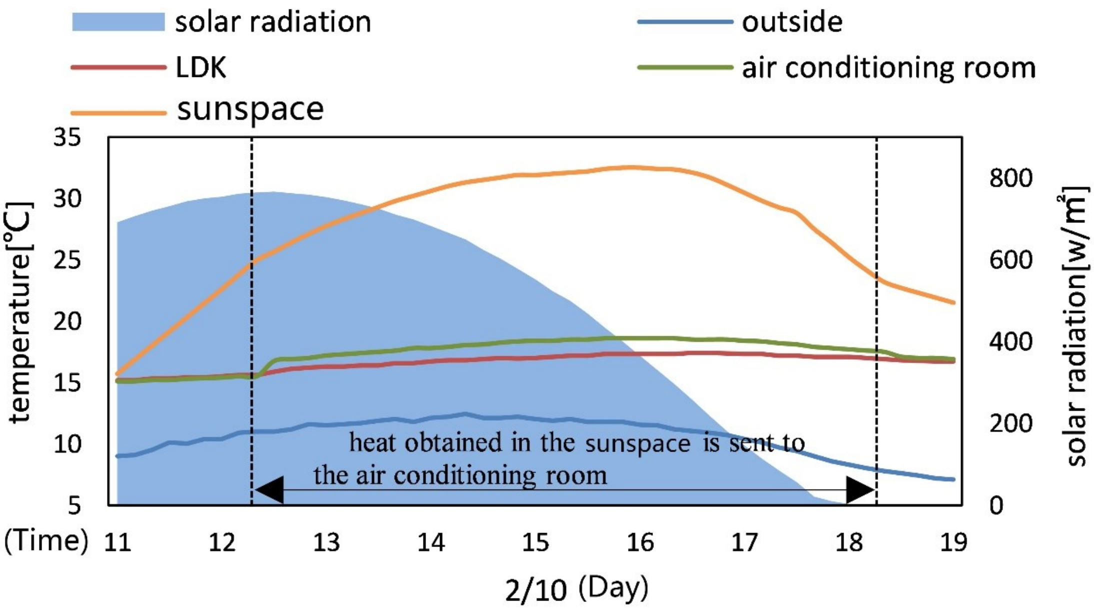

Figure 3.2 Each room temperature when air is being sent from inside the sunspace (without air conditioning)

3.4. Simulation results

3.4.1. Verify the accuracy of the simulation software

In order to verify the case by experiment, the measured meteorological data of Miyazaki is configured as a data input file of the simulation program based on the state of the demonstration house. The time step is ten minutes. The experiment was carried out with air conditioning all day. Figure 3.3 is the calculated data and monitored data of the temperature inside the sunspace. Figure 3.4 is the calculated data and monitored data of the temperature of the child room. The fact that the simulated temperatures roughly match the actual ones confirms that the simulation software is highly accurate.

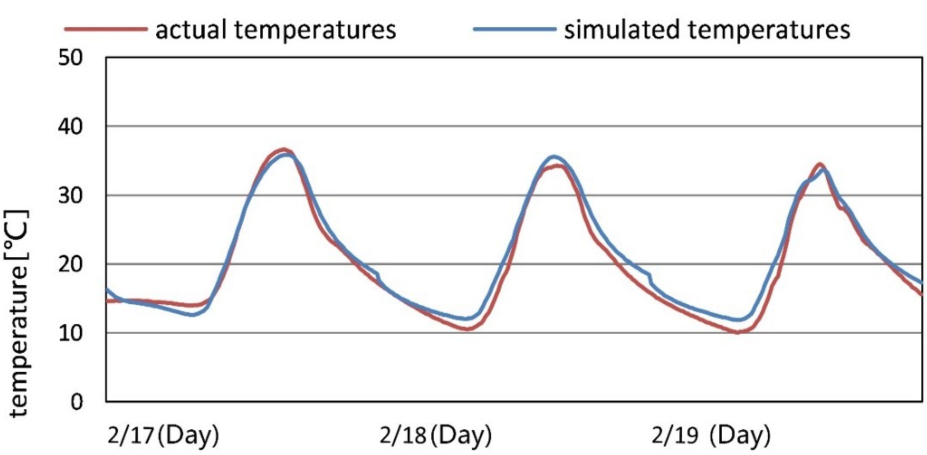

Figure 3.3 The calculated data and monitored data of the temperature inside the sunspace

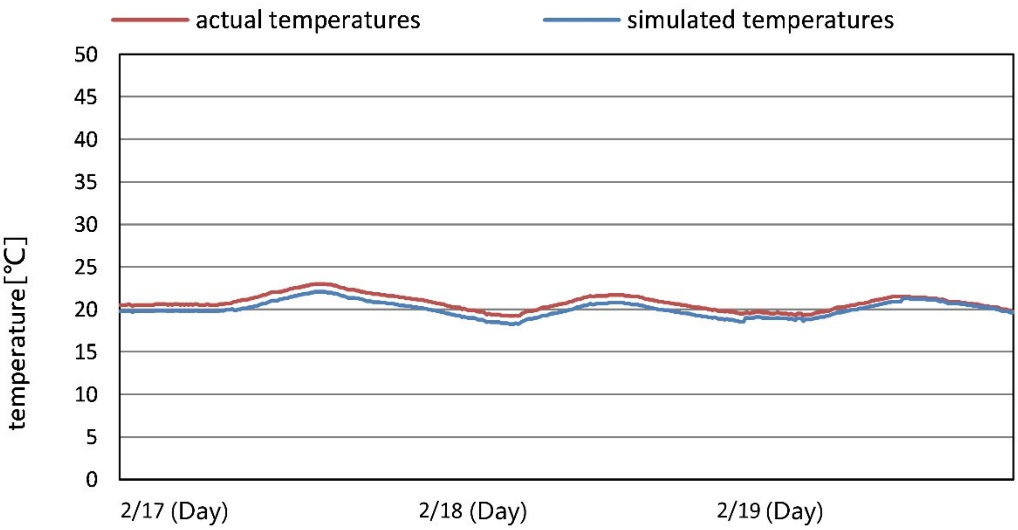

Figure 3.4 The calculated data and monitored data of the temperature of the child room

3.4.2. Reduce heating load by using heat collected from the sunspace

Figure 3.5 shows the monthly heating load in cases I, II and III, and Table 3.3 shows the monthly heating load reduction ratio. The unit of load reduction ratio is percentage.

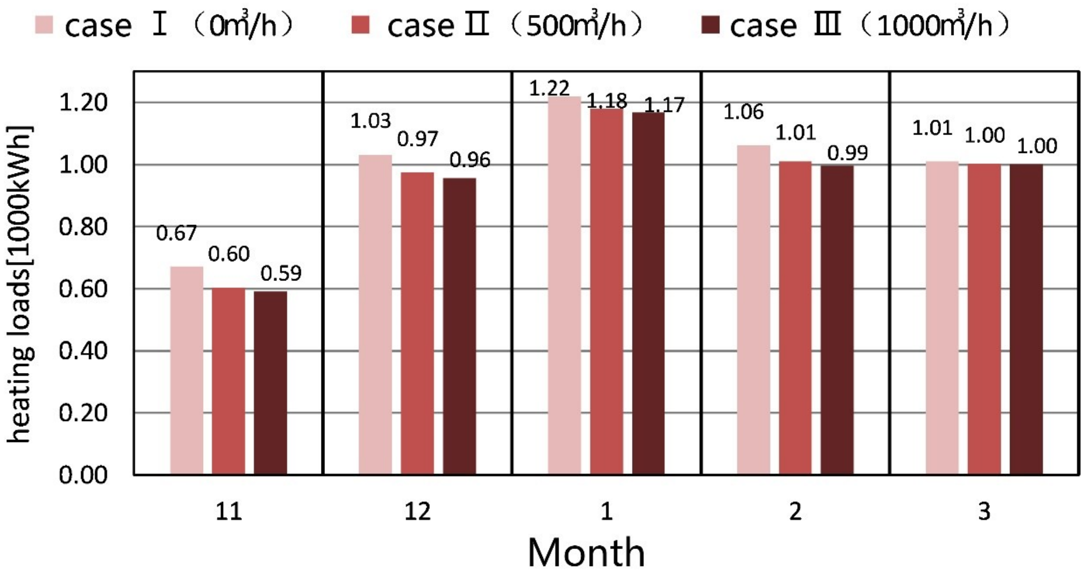

Figure 3.5 The monthly heating load (I, II and III)

Table 3.3 The monthly heating load reduction ratio (%)

	500 [m^3/h]	1000 [m^3/h]	margin
Total	4.03	5.12	1.08
November	9.96	11.86	1.90
December	5.64	7.29	1.65
January	3.35	4.39	1.04
February	4.80	6.27	1.47
March	0.64	0.77	0.14

In all months, airflow of 500 m^3/h or 1000 m^3/h from the sunspace to the air conditioning room reduced the heating load more than airflow of 0 m^3/h, confirming that airflow from the sunspace helps to reduce the heating load. However, the heating load reduction ratio was extremely low in March, when sending air from inside the sunspace to the air conditioning room did not have any effect on the heating load because there are many cloudy days causing the sunspace temperature to not be very high. Further, comparing airflow of 500 m^3/h from inside the sunspace to the air conditioning room with airflow of 1000 m^3/h, the fact that the difference in heating load reduction ratios was about 1% throughout the period indicates that 500 m^3/h, the volume currently used, is sufficient. For real application, we can change the amount of airflow to 500 m^3/ h.

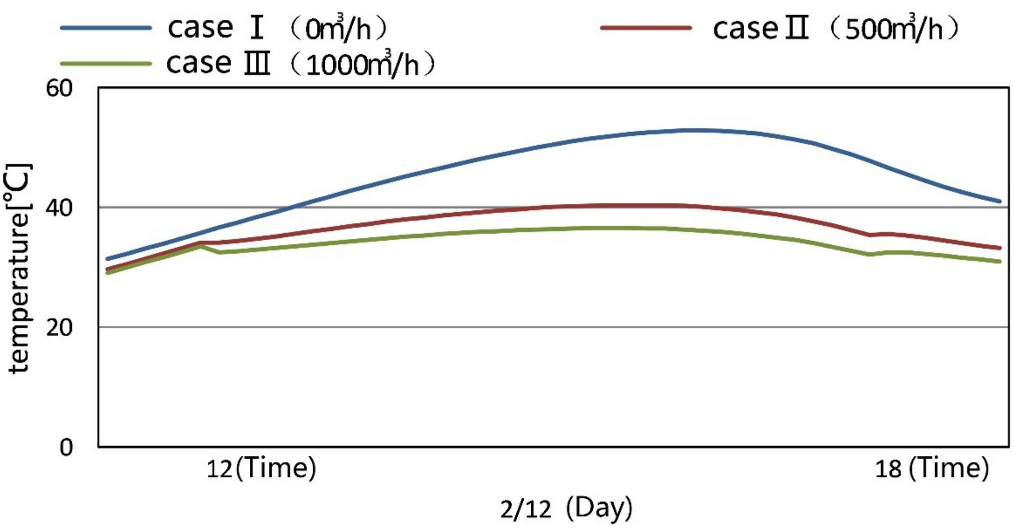

Figure 3.6 The variation in the temperature inside the sunspace on sunny days (I, II and III)

Figure 3.6 shows the variation in the temperature inside the sunspace on sunny days in cases I, II and III. The temperature inside the sunspace was lower when there was airflow from the sunspace to the air conditioning room (cases II, III) than when there was no airflow (case I). However, in all cases the temperature inside the sunspace was high, at 30 °C or more, indicating that investigation is needed into more effective ways of using the heat collected inside the sunspace.

Figure 3.7 shows the yearly heating load in cases II and IIc. The yearly heating load in case IIc, where a thermal storage medium was installed under the floor inside the sunspace, was reduced by about 5% to approximately 250 kWh, lower than that in case II where there was no thermal storage. This demonstrates that using high heat capacity flooring materials inside the sunspace further enhances the heating load reduction effect of airflow from inside the sunspace to the air conditioning room.

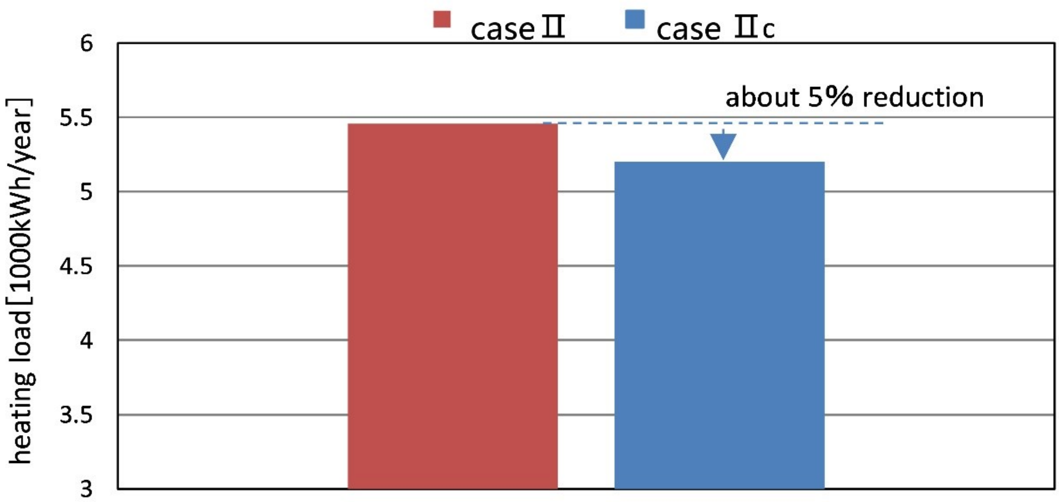

Figure 3.7 The yearly heating load in cases II and IIc

Figure 3.8 shows changes over two days in the temperature inside the sunspace in case II and case IIc. Given that the temperature inside the sunspace drops more slowly at night when a thermal storage medium is installed in its floor, it may be possible to further reduce the heating load by extending the period of airflow from the sunspace to the air conditioning room.

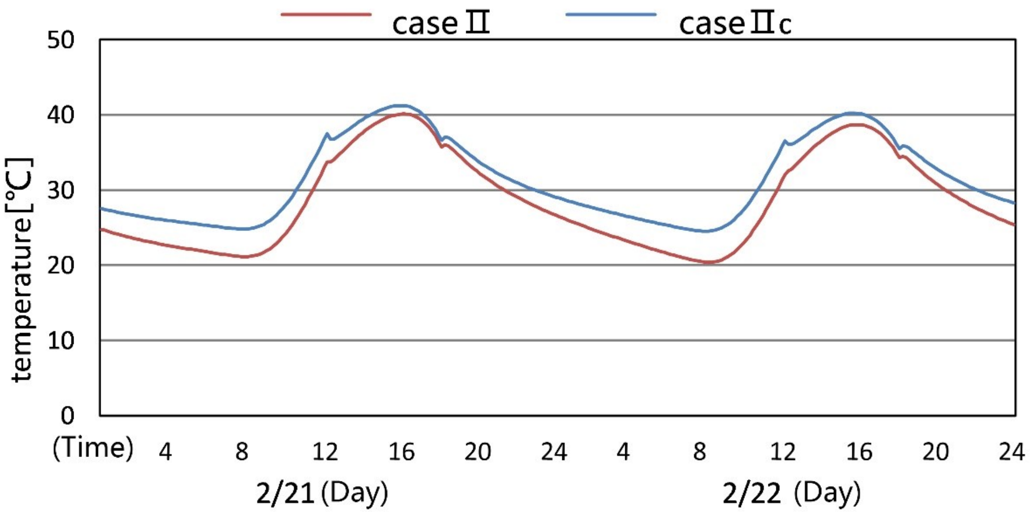

Figure 3.8 Changes over two days in the temperature inside the sunspace (II and IIc)

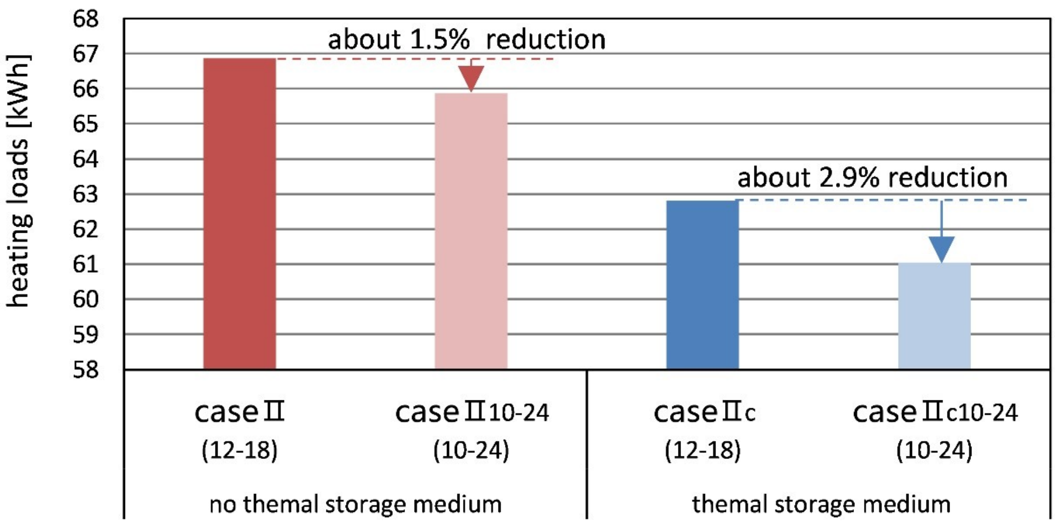

Figure 3.9 The heating loads over two days when the period of airflow from the Sunspace to the air conditioning room was extended (II and IIc)

Figure 3.9 shows the heating loads in cases II and IIc over two days when the period of airflow from the sunspace to the air conditioning room was extended. The airflow period was extended to last from 10:00 to 24:00. It can be concluded that extending the duration of airflow had a greater impact on the heating load ratio in the presence of a thermal storage medium because of using high heat capacity flooring materials. For real application, we can add high heat capacity material to the existing storage wall and extended the airflow period.

3.4.3. Investigation without air conditioning

We investigated whether it was possible to keep the LDK (living room/dining room/kitchen) area at a comfortable temperature without the use of heating by only using the airflow from inside the sunspace. Figure 3.10 shows temperature distribution in the LDK (living room/dining room/kitchen) areas of cases V, VI and VIc from December to March. In this study, a comfortable interior temperature was defined as being between 18°C and 22°C [72]. It comes from one of Japan's thermal comfort standard in winter. In all cases, temperatures were below the comfortable range at least 90% of the time, showing that it is difficult to keep the LDK (living room/dining room/kitchen) area at a comfortable temperature without using heating.

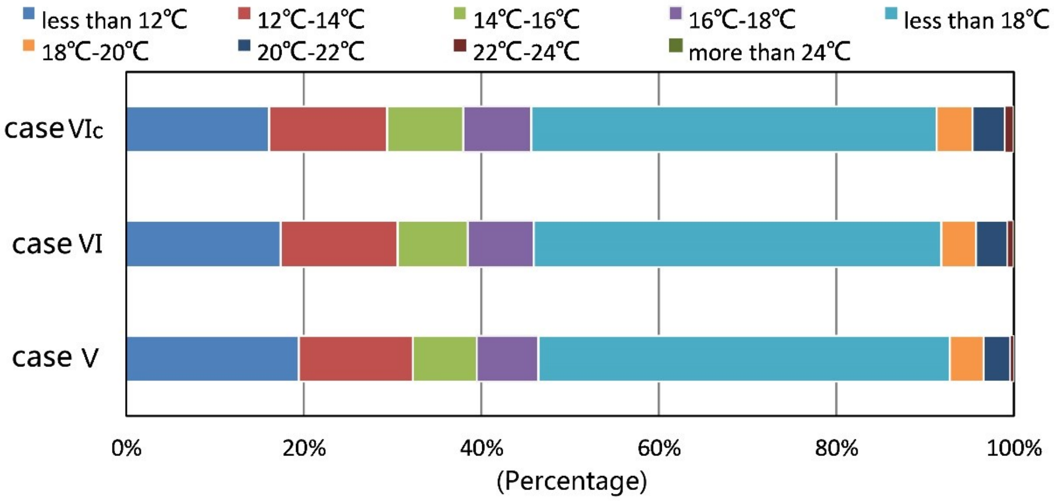

Figure 3.10 Temperature distribution in the LDK (living room/dining room/kitchen) areas from December to March (V, VI, and VIc)

As one method of making effective use of the air inside the sunspace, we investigated the effectiveness of keeping the window open in the second-floor bedroom bordering the sunspace and letting the heat from the sunspace circulate into that room. Figure 3.11 shows the second-floor bedroom's temperature and sunspace temperature over one day in cases VIc, VIcw, and VIcw 24 hr. Note that case VIcw 24Hr is the same as case VI except that the window was left open for 24 hours. Because the open window in the second-floor bedroom allowed the collected heat to directly enter the room, the temperatures in the sunspace were lower in cases VIcw and VIcw 24hr than they were in Case VIc, where the windows were closed. Further, when the windows were open, the second-floor bedroom reached a comfortable temperature (18°C to 22°C) between 17:00 and 20:00, with the temperature in case VIcw 24hr remaining approximately 1°C to 3°C higher than in case VIc. These results demonstrate that by opening the window next to the sunspace, the heat inside the sunspace can be used efficiently and the second-floor bedroom can, at times, reach a comfortable temperature. However, the time of day when the open inside window to the sunspace allowed the second-floor bedroom to reach a comfortable temperature was between approximately 17:00 and 20:00, a time when the second-floor bedroom was unoccupied. It can be concluded that if the LDK (living room/dining room/kitchen) area was positioned on the second floor next to the sunspace, opening the window of the sunspace would allow the LDK (living room/dining room/kitchen) area to be kept warm without the use of heating for more of the time that the area is occupied. For real application, we can add the sunspace to the south of living/dining/kitchen area.

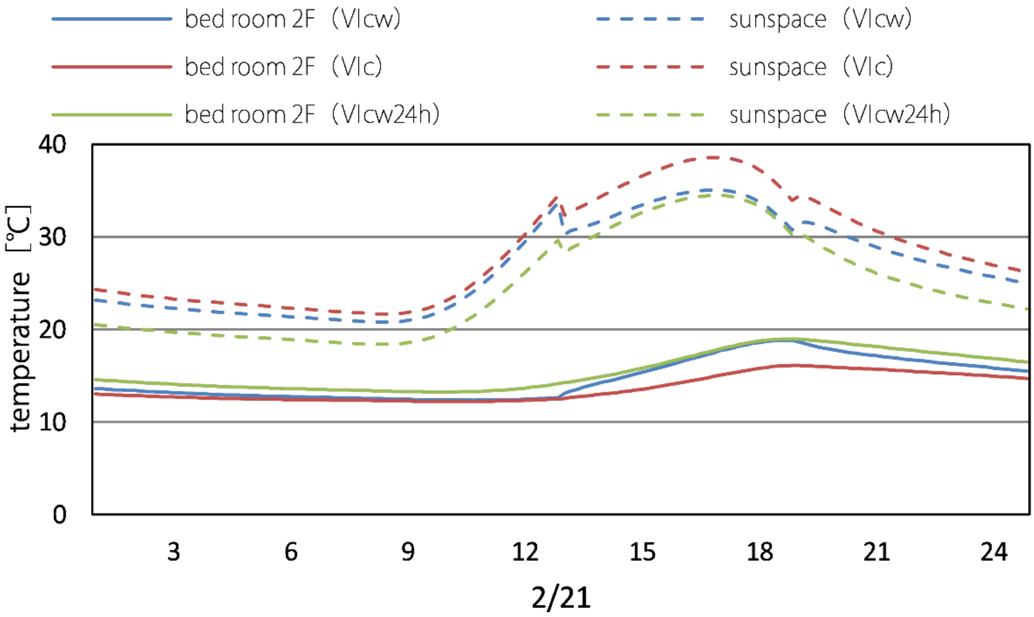

Figure 3.11 The second-floor bedroom temperature and sunspace temperature over one day (VIc, VIcw, and VIcw 24 hr.)

3.4.4. Investigation with intermittent air conditioning

Because it is difficult to keep the LDK (living room/dining room/kitchen) area warm without heating, we ran a simulation with intermittent air conditioning. Figure 3.12 shows changes in temperature over one day in the LDK (living room/dining room/kitchen) area of case IV. The fact that the temperature stayed at more or less 20°C even after the air conditioning was stopped indicates that, on days when the temperature inside the sunspace is high, the airflow from the sunspace is enough to keep the area at a comfortable temperature in the afternoon. For the real applications, the air conditioner can be turned off when the heat is sent from the sunspace to the air conditioning room on sunny days.

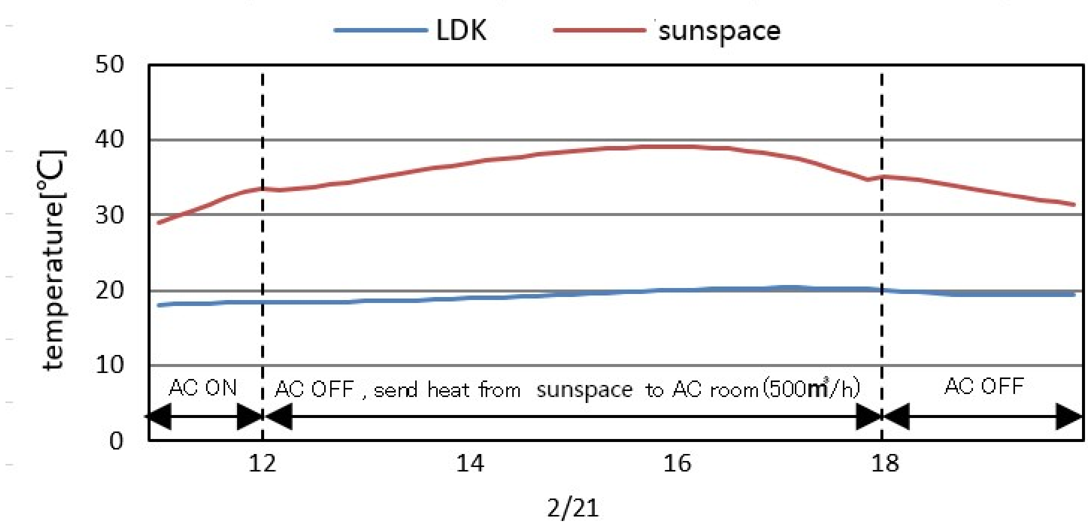

Figure 3.12 Changes in temperature over one day in LDK (IV)

3.5. Summary

We conducted an actual survey to understand the situation of heat utilization of the sunspace and used numerical simulations to examine the effective method of heat utilization of the sunspace. These are our findings:

(1) When air conditioning is used all day, the heating load can be reduced by combining heat collected inside the sunspace with duct-style central air conditioning. However, we confirmed that, under normal use, the temperature inside the sunspace remains high even if the air is circulated, resulting in overheating.

(2) Raising the sunspace's ability to store heat leads to a gentler drop in its nighttime temperature, enabling an extension of the period during which airflow is circulated in the air conditioning room.

(3) When air conditioning is not used, there are times when the rooms bordering the sunspace can be heated to a comfortable temperature by opening the windows to the sunspace during the daytime; it can, therefore, be concluded that it is preferable to position the main living areas next to the sunspace.

(4) When intermittent air conditioning is used, on sunny days, the living room/dining room/kitchen area can be kept at a comfortable temperature even after the air conditioning has been stopped by only using the airflow from inside the sunspace.

Chapter 4.

Experimental analysis of thermal performance

4. Experimental analysis of thermal performance

4.1. Experimental procedure

We studied the thermal effects and operation methods of the sunspace by using measurements. In this study, from February 2015 to 2016, we measured the temperature and moisture of each room and the sunspace using the RTR-503 device. The time step is ten minutes. The air is sent to the central air conditioning room from a sunspace only when the temperature inside the sunspace is above 24 °C. The air circulation between the sunspace and central air conditioning room is 500 m^3/h. The air circulation between the each room and central air conditioning room is 840 m^3/h for the LDK (living/dining/kitchen), 560 m^3/h for the child's room and the bedroom, and 150 m^3/h for the others.

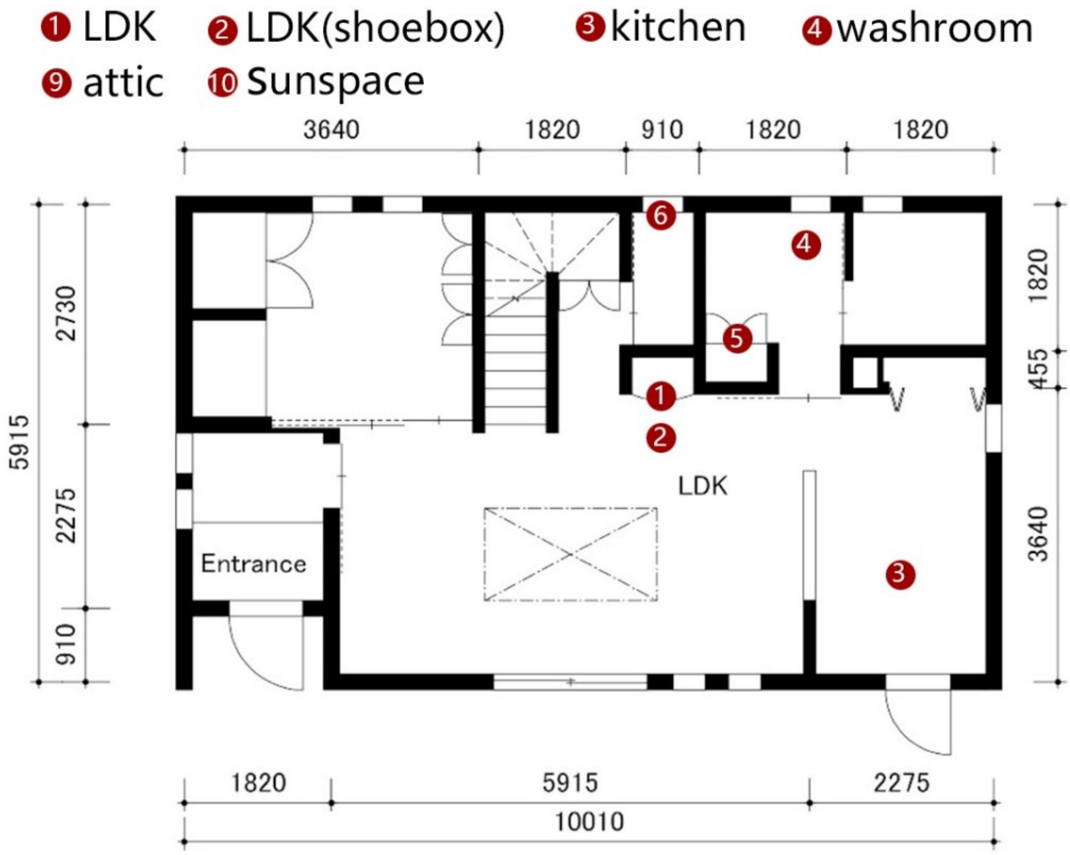

Figure 4.1 The measurement points of 1st floor

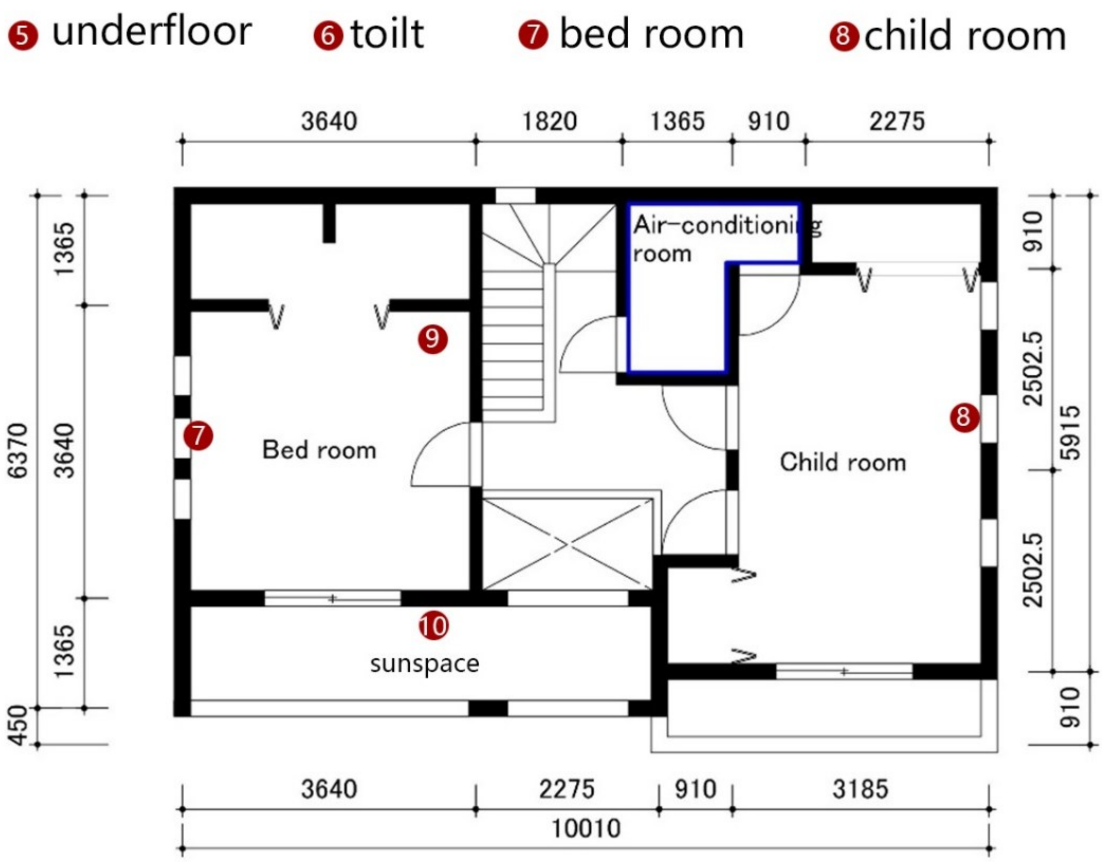

Figure 4.2 The measurement points of 2nd floor

Figures 4.1 and 4.2 show the floor plans and the temperature measurement points. The height of the sensors were at the middle height of each space. The experimental work introduced here mainly focuses on the analysis of the performance of the sunspace, when the air is sent to the air conditioning room from the air cavity of the sunspace.

4.2. Results and discussion

4.2.1. Analysis of thermal environment in winter

We measured the results of March 2015 and results from November 2015 to February 2016. Figures 4.3, 4.4, 4.5, 4.6 and 4.7 show the changes in the temperature of each room and the outside air. During the period from March 1st to 8th, the air conditioning is turned on (the setting temperature of the air conditioner is 20 °C), and the air in the sunspace is sent to the air conditioning room when the sunspace temperature exceeds 24°C. From March 9th to 31st, from November 1th to 24th, the air conditioning is turned off, and the air in the sunspace is sent to the air conditioning room when the temperature in the sunspace exceeds 24°C. During the period from November 25 to February 29, the air conditioning is turned on (the setting temperature of the air conditioner is 22 °C), and the air in the sunspace is sent to the air conditioning room when the sunspace temperature exceeds 24°C.

In November, December, January, and February, in some days the temperature in the sunspace exceeds 40°C, and 70% of the days exceed 30°C in 4 months. Even if the air in the sunspace is sent to the air conditioning room, the temperature in the sunspace is still high, so the heat in the sunspace can be further utilized. Even in December, January and February when the outside temperature is low, the heat in the sunspace can be used to reduce the heating load because the temperature in the sunspace reaches a high temperature during the daytime.

In November, December, January, February and March, the proportion of days in which days in which sunspace temperature over 24 °C (the control temperature when the air in the sunspace is sent to the air conditioning room) was 49%, 40%, 20%, 32% and 29% respectively (Table 4.1). In other words, even if the air is sent to the air conditioning room during the time when the temperature in the sunspace exceeds 24°C, the number of days in the sunspace where the temperature exceeds 24°C accounts for a large proportion. Therefore, it can be said that the heat in the sunspace cannot be sufficiently utilized only by sending the air in the sunspace to the air conditioning room. Therefore, it is necessary to consider ways to further use the heat inside the sunspace, such as adding additional thermal storage in the sunspace.

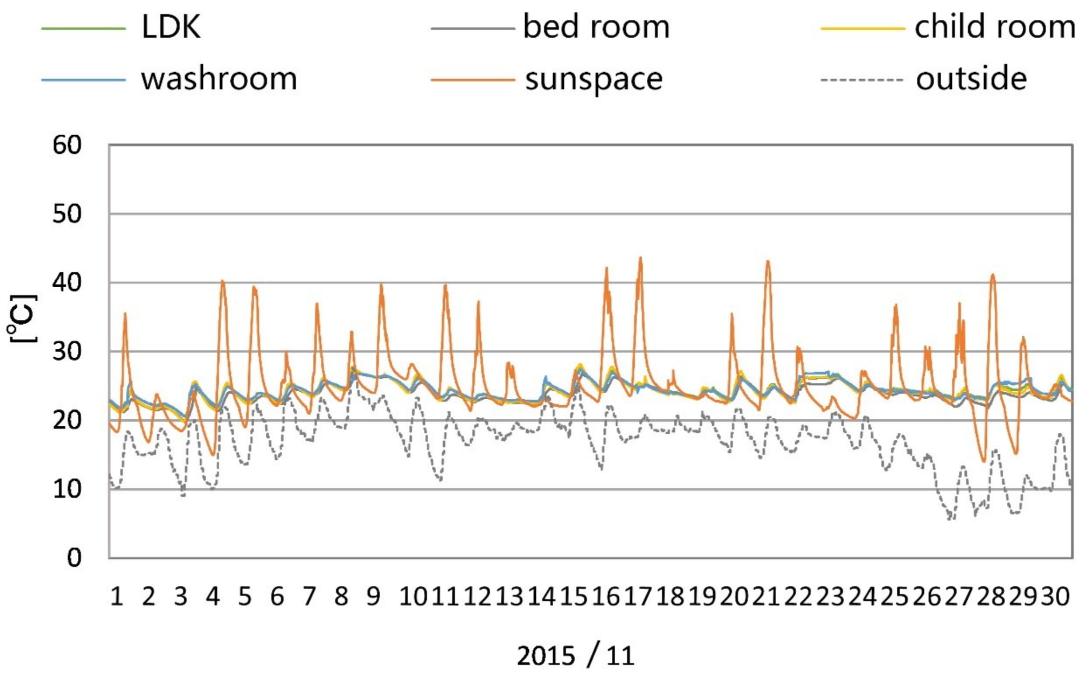

Figure 4.3 Each room temperature and outdoor air temperature (November)

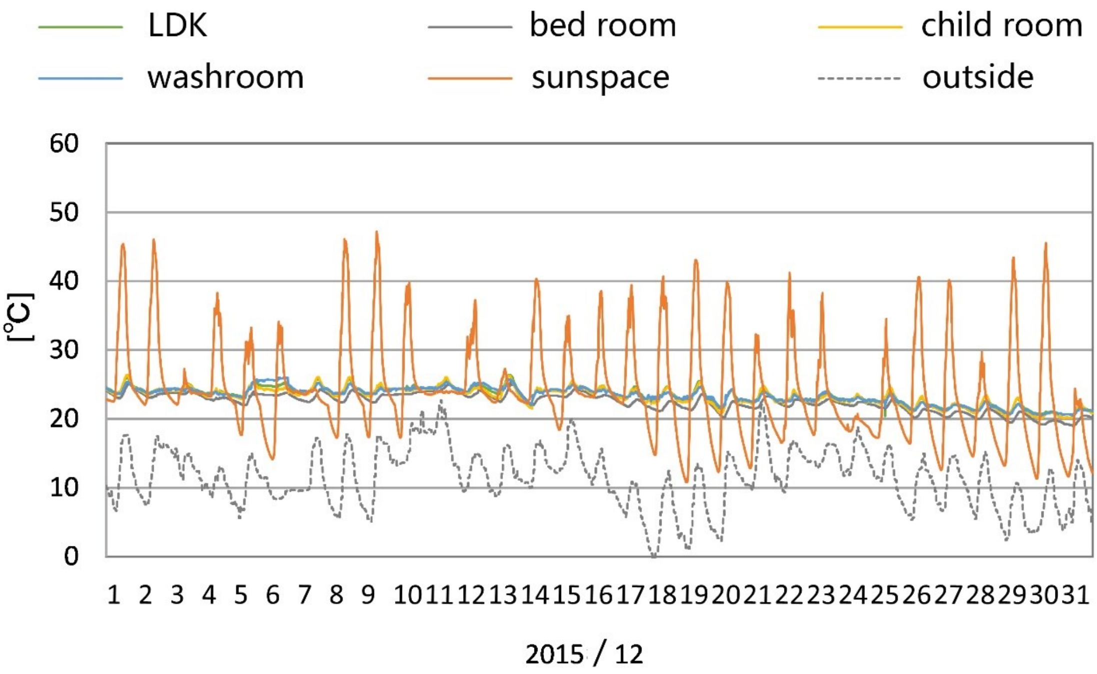

Figure 4.4 Each room temperature and outdoor air temperature (December)

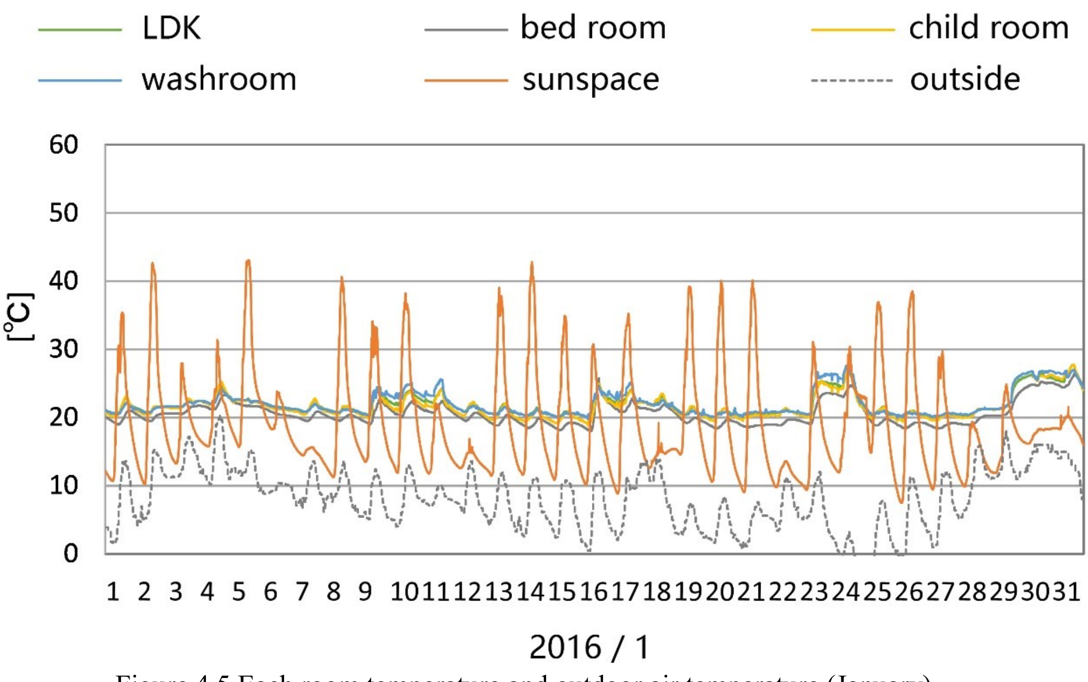

Figure 4.5 Each room temperature and outdoor air temperature (January)

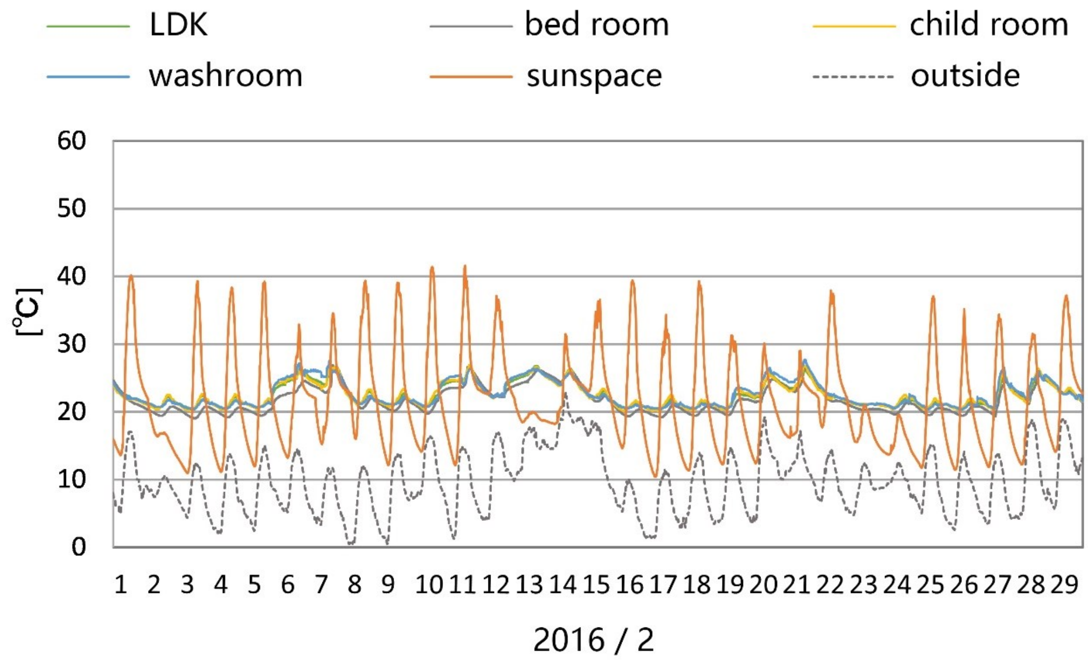

Figure 4.6 Each room temperature and outdoor air temperature (February)

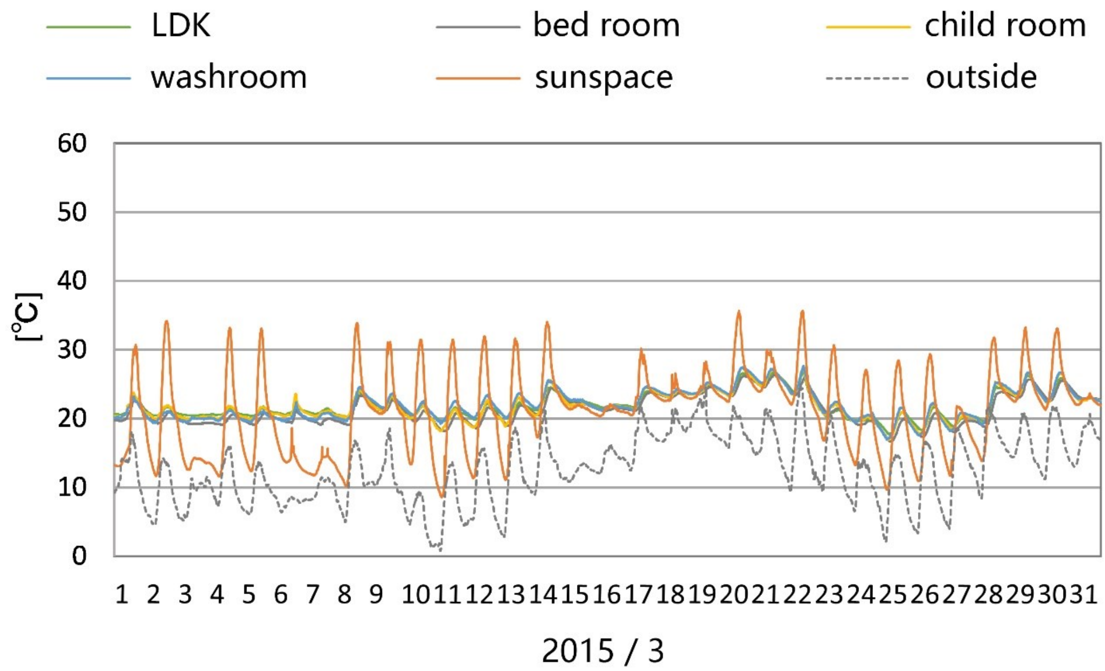

Figure 4.7 Each room temperature and outdoor air temperature (March).

Table 4.1 The proportion of days in which sunspace temperature over 24 °C

	Nov.	Dec.	Jan.	Feb.	Mar.
sunspace	49%	40%	20%	32%	29%

Table 4.2 The proportion of days in which the temperature of each room exceeds 20 °C

	Nov.	Dec.	Jan.	Feb.	Mar.
LDK	100%	100%	100%	100%	90%
washroom	100%	100%	100%	100%	90%
children	100%	100%	90%	100%	87%
bedroom	100%	94%	67%	82%	67%

In November, December, January and February, the proportion of days in which LDK (living /dining/kitchen) room temperature above 20 °C was 100%, but in March it was 90% (Table 4.2). Since the air conditioning room temperature in March was set at 20 °C, the temperature in each room was lower than 20 °C because the air was sent to each room from the air conditioning room. In addition, from March 9 to 31, the LDK (living /dining/kitchen) room temperature is lower than 20°C because the air conditioner is turned off. However, air conditioning is not used from November 1 to 24, but the LDK (living /dining/kitchen) room temperature in November maintains a comfortable temperature (18°C to 22°C [72]). In November, the outdoor temperature is higher than in March, so the temperature of the LDK (living /dining/kitchen) room can be kept comfortable by sending hot air from the sunspace to the air conditioning room.

In November, December, January and February, the proportion of days in which washroom temperature above 20 °C was 100%, but in March it was 90% (Table 4.2). The reason why the percentage of washroom above 20 °C in March is lower than other months is the same reason as the LDK (living /dining/kitchen) room. In addition, since the LDK (living /dining/kitchen) room is located on the south side, and the washroom is located on the north side, affected by solar radiation, the percentage of temperatures above 20 °C in the washroom in March is lower than that of the LDK (living /dining/kitchen) room.

The ratio of the temperature of the children's room above 20 ° C is about 100% in November, December and February, 90% in January and 87% in March (Table 3). The ratio of the bedroom temperature above 20 ° C is about 100% in November, 94% in December, about 67% in January, 82% in February and 67% in March (Table 4.2). The percentage of temperatures above 20 °C in the bedroom is lower than that of the children's room. It can be seen that until the outside air temperature reaches the maximum as shown in Figure 4.7 (March 10 to 13), the children's room has a higher temperature than the bedroom, and at night the temperature of the bedroom is higher than that of the children's room. It can be considered that this is influenced by the orientation (east and west). Therefore, due to the influence of solar radiation, when the outdoor air temperature in the morning becomes lower, the temperature of the children's room rises faster than the bedroom temperature, and therefore the ratio of the bedroom temperature above 20°C is lower than that in the children room.

Figures 4.8 and 4.9 show the temperature of each room, the temperature of the outside air, and solar radiation. In sunny days, due to the large temperature difference between daytime and nighttime, and the large amount of solar radiation during the daytime, the temperature difference between daytime and nighttime in sunspace is relatively large. The difference on February 4 is 27.2 °C. As the hot air in the sunspace is sent to the air conditioning room, the temperature in each room increases as the temperature of the sunspace rises. When the amount of solar radiation is relatively small on a rainy day, the temperature difference in the sunspace is relatively small. The difference on February 13 is 3.25 °C. When the temperature in the sunspace is lower than 24°C, the air in the sunspace will not be sent to the air conditioning room, so the central air conditioning machine can keep the temperature of each room at a constant temperature, and the temperature rises as the outdoor air temperature rises.

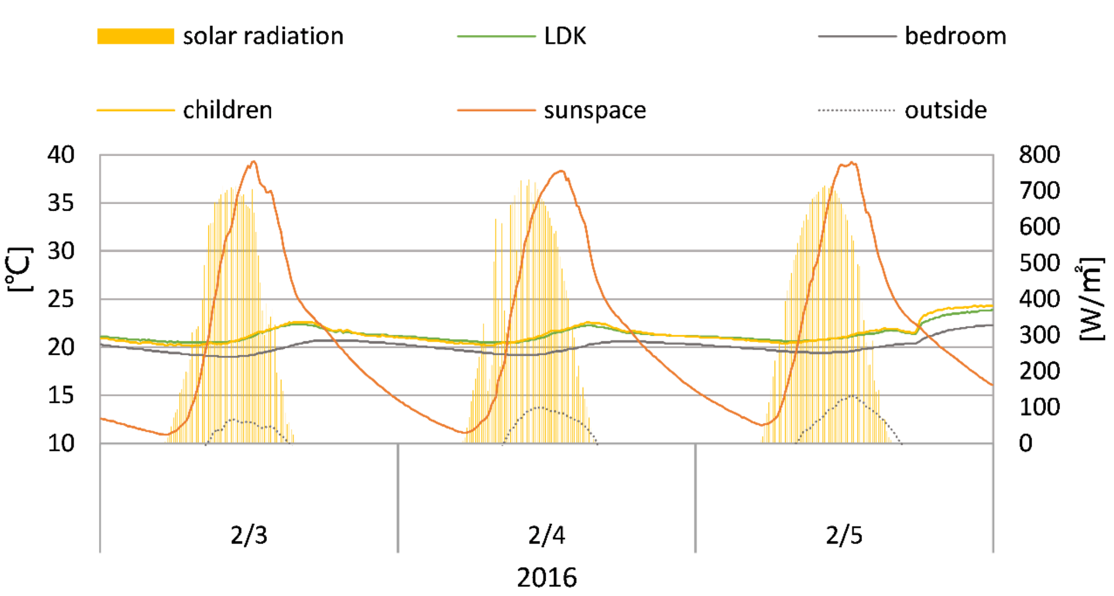

Figure 4.8 Each room and outdoor air temperature and solar radiation (3 sunny days in February)

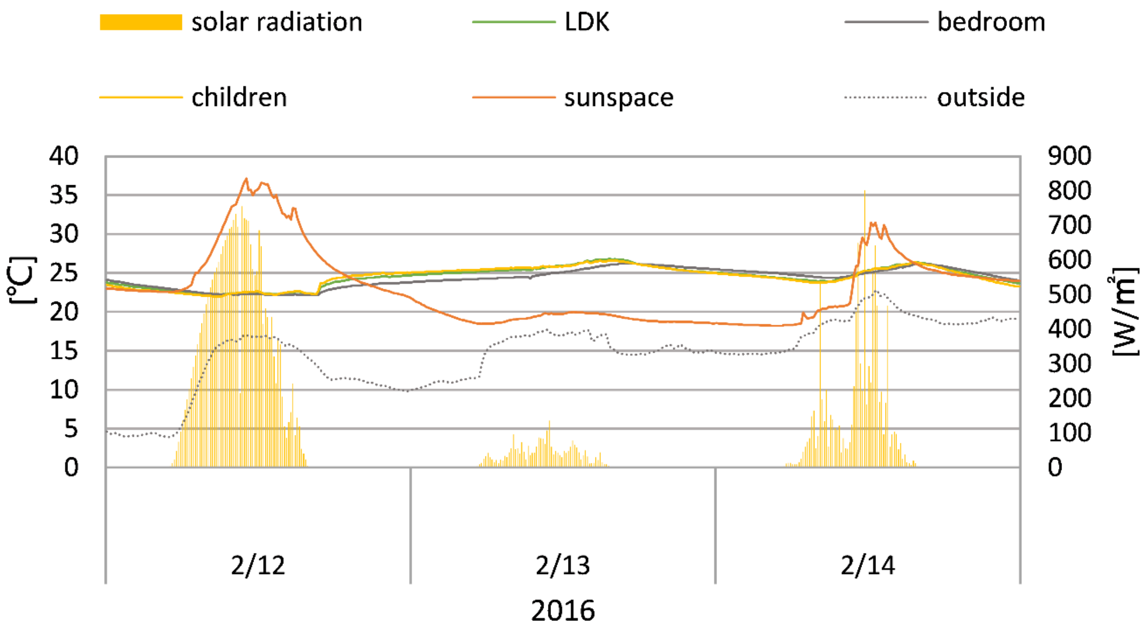

Figure 4.9 Each room and outdoor air temperature and solar radiation (3 rainy days in February)

4.2.2. Analysis of the thermal environment in the intermediate period

Figures 4.10, 4.11 and 4.12 show the temperature of each room and the temperature of the outside air. From April 1 to 26, the air conditioning is turned off, and the air in the sunspace is sent to the air conditioning room when the temperature in the sunspace exceeds 24°C. From April 27 to June 19, the air conditioning is turned off, and the air in the sunspace is not sent to the air conditioning room. After June 20, the air conditioning was turned on (dehumidification, the air conditioning temperature was set at 27 °C), and the outside window of the sunspace was opened.

In April and May, the temperature in the sunspace does not exceed 40 °C, and the temperature difference between daytime and nighttime in the sunspace is not large. This is because the outdoor temperature rises and the amount of incident solar radiation decreases. From April to May, about 60% of the days in the sunspace have a temperature of more than 30°C, which is 10% lower than in winter. In April and May, the solar altitude became larger and the amount of solar radiation was less than in winter. In April and May, the proportion of days in which sunspace temperature over 24 °C (the control temperature when the air in the sunspace is sent to the air conditioning room) was 48% and 71% respectively. Compared with winter, the proportion has increased. It can be concluded that as the outside air temperature rises, the temperature in the sunspace rises as a whole.

From June 1 to June 19, the difference between the temperature in the sunspace and the outdoor air temperature was small, although the outside windows of the sunspace were closed. This is because outside temperatures rise and the amount of incident solar radiation is less than winter. In addition, it is the rainy season, which has many rainy days, and there is not enough radiation to increase the sunspace temperature. However, there is a small difference between the sunspace temperature and the outside temperature, which indicates that the night temperature drops less. This confirms that the heat accumulated during the day is stored in the sunspace.

In all rooms, the proportion of days in which temperatures exceeding 20°C was 91% in April, 100% in May, and 97% in June. From April 6 to 10 (cloudy or rainy), the outdoor air temperature was low, and the temperature in the sunspace was less than 20°C. On June 24 to 27, the room temperature is lower than the outside air temperature. It is considered that the set temperature of dehumidification was lowered. From April 1 to 26 (the air conditioning was turned off), even if the outdoor temperature is lower than 20 °C, each room is kept comfortable only by sending the heat from the sunspace to the air conditioning room. Therefore, in the intermediate period, the use of a combination of sunspace and central air circulation system can maintain the thermal environment of each room.

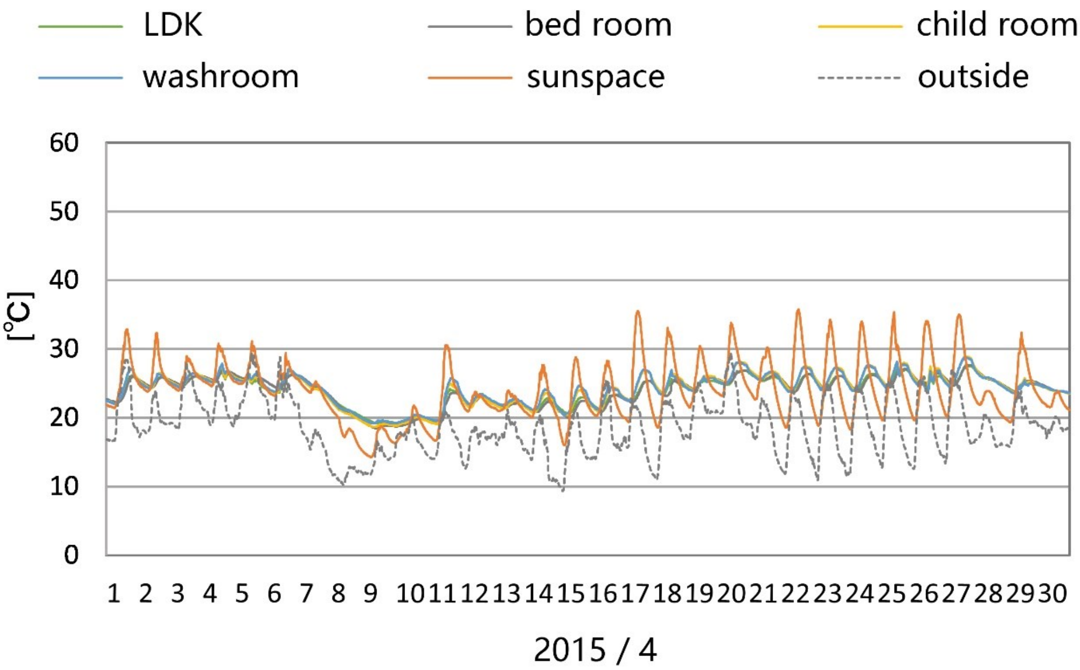

Figure 4.10 Each room temperature and outdoor air temperature (April)

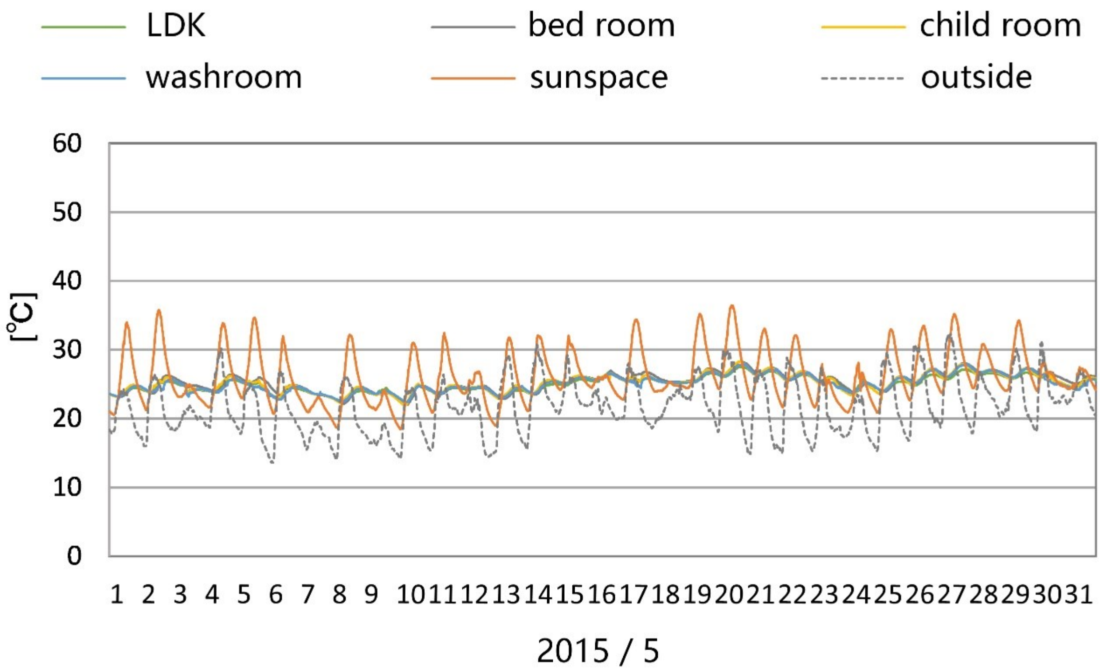

Figure 4.11 Each room temperature and outdoor air temperature (May)

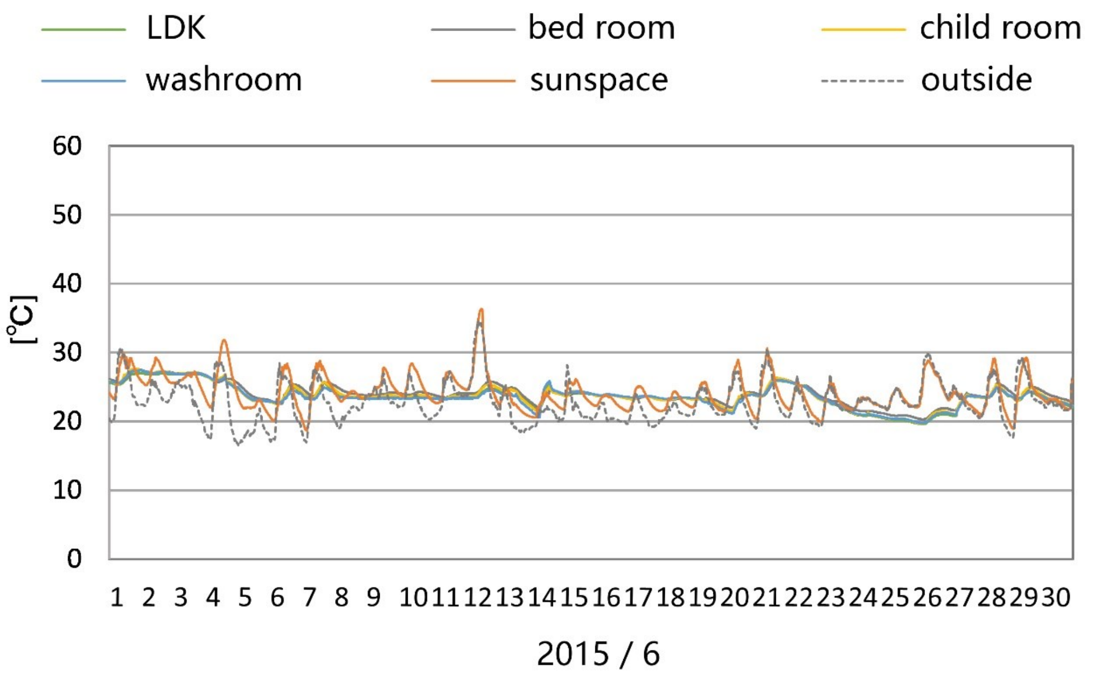

Figure 4.12 Each room temperature and outdoor air temperature (June)

Figures 4.13 and 4.14 show the temperature of each room, the temperature of the outside air, and solar radiation. In sunny days, due to the large temperature difference between daytime and nighttime, and the large amount of solar radiation during the daytime, the temperature difference between daytime and nighttime in sunspace is relatively large. The difference on April 26 is 14.4 °C. On April 25 and 26, the air in the sunspace was sent to the air conditioning room, and the temperature in each room fluctuates greatly. On April 27, the temperature in each room moderately changed because the air in the sunspace was not sent to the air conditioning room. When the amount of solar radiation is relatively small on a rainy day, the temperature difference in the sunspace is relatively small. The difference on April 4 is 6.2 °C. When the temperature in the sunspace is lower than 24°C, the air in the sunspace will not be sent to the air conditioning room, so the central air conditioning machine can keep the temperature of each room at a constant temperature, and the temperature rises as the outdoor air temperature rises. However, even in the rainy days, the temperature in the sunspace will exceed 24°C. It can be concluded that the heat in the sunspace can be used during the intermediate period.

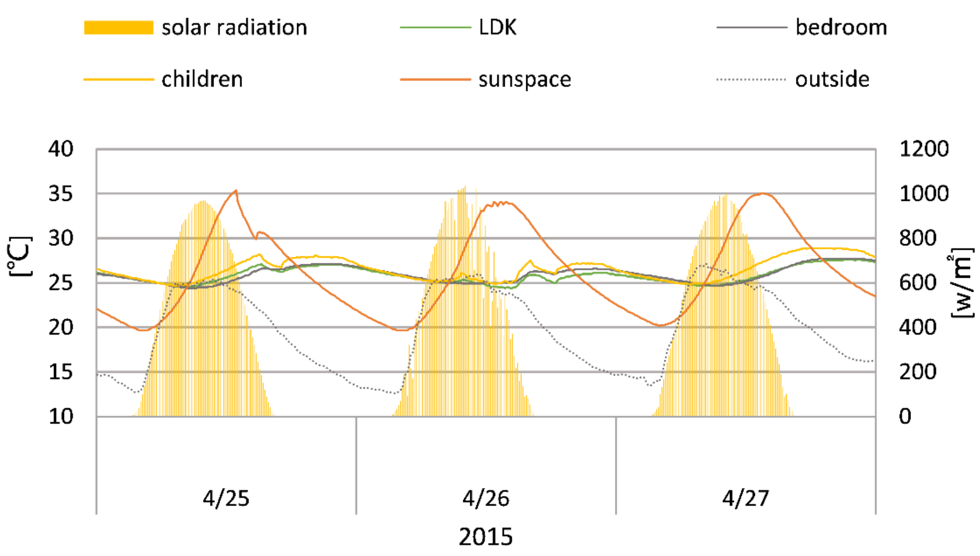

Figure 4.13 Each room and outdoor air temperature and solar radiation (3 sunny days in April)

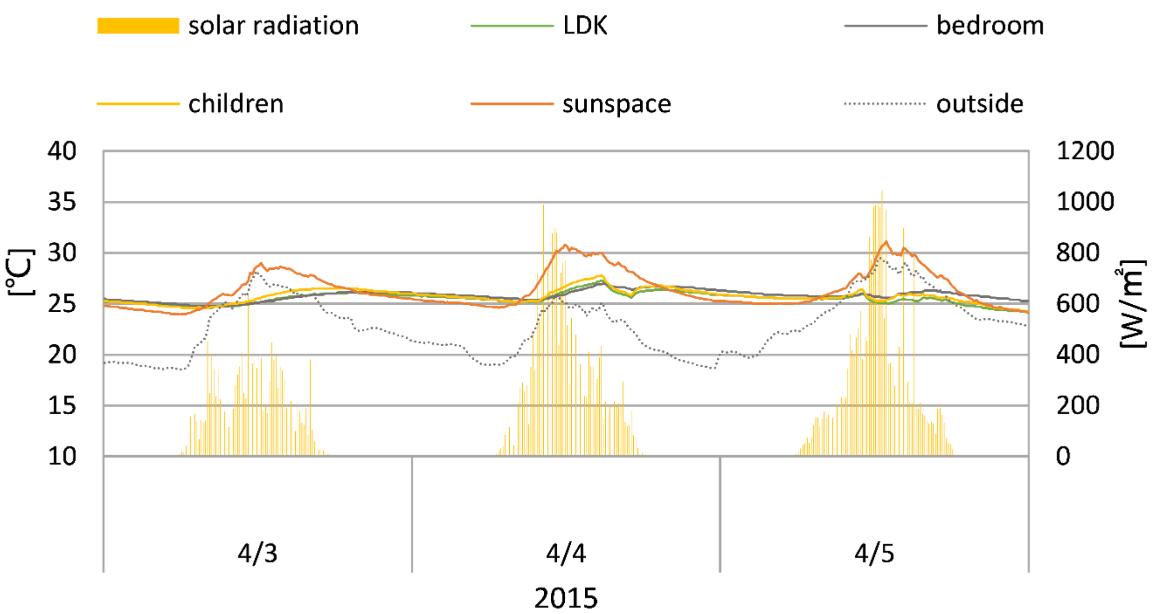

Figure 4.14 Each room and outdoor air temperature and solar radiation (3 rainy days in April)

4.2.3. Analysis of thermal environment in summer

Figures 4.15, 4.16, 4.17 and 4.18 show the temperature of each room and the temperature of the outside air. From July 1 to 23, the air conditioning with dehumidification function was turned on (the air conditioning temperature was set at 27 °C), and the outside window of the sunspace was opened. From August 23 to October 16, the air conditioning was turned on (cooling, the air conditioning temperature was set at 26 °C), and the outside window of the sunspace was closed. At this time, the air in the sunspace is sent to the air conditioning room only during the time when the temperature in the sun room is lower than 24 °C. From October 17 to 30, the air conditioning is turned off, and the air in the sunspace is sent to the air conditioning room when the temperature in the sunspace exceeds 24°C. From August 23 to 31, September, and October 1 to October 16, the ratio of temperatures below 24°C in the sunspace was 0%, 8%, and 1%, respectively.

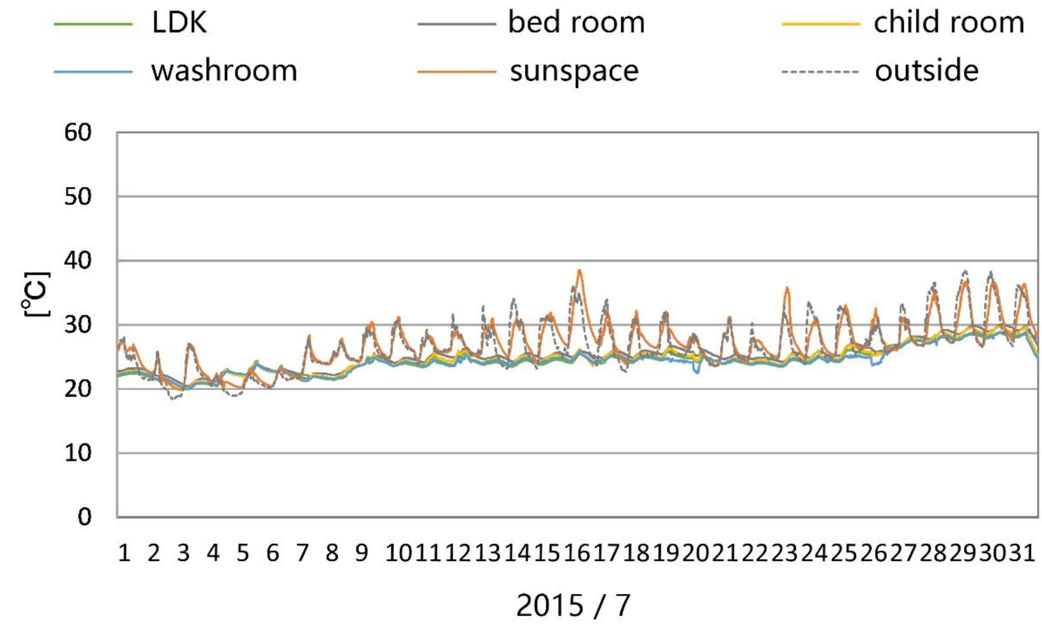

Figure 4.15 Each room temperature and outdoor air temperature (July)

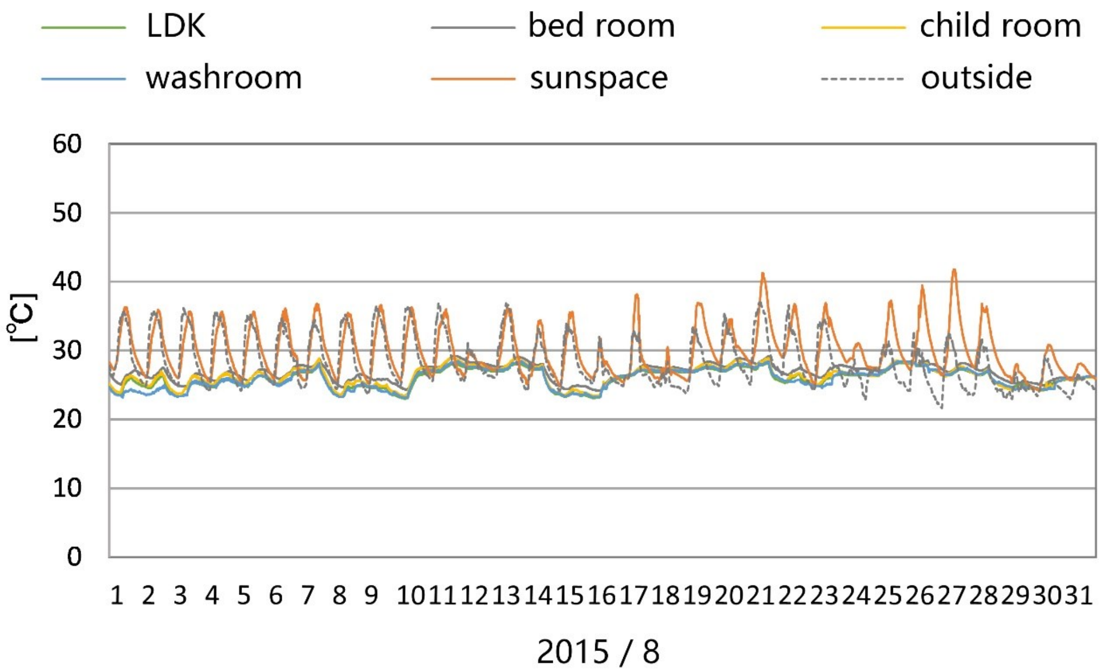

Figure 4.16 Each room temperature and outdoor air temperature (August)

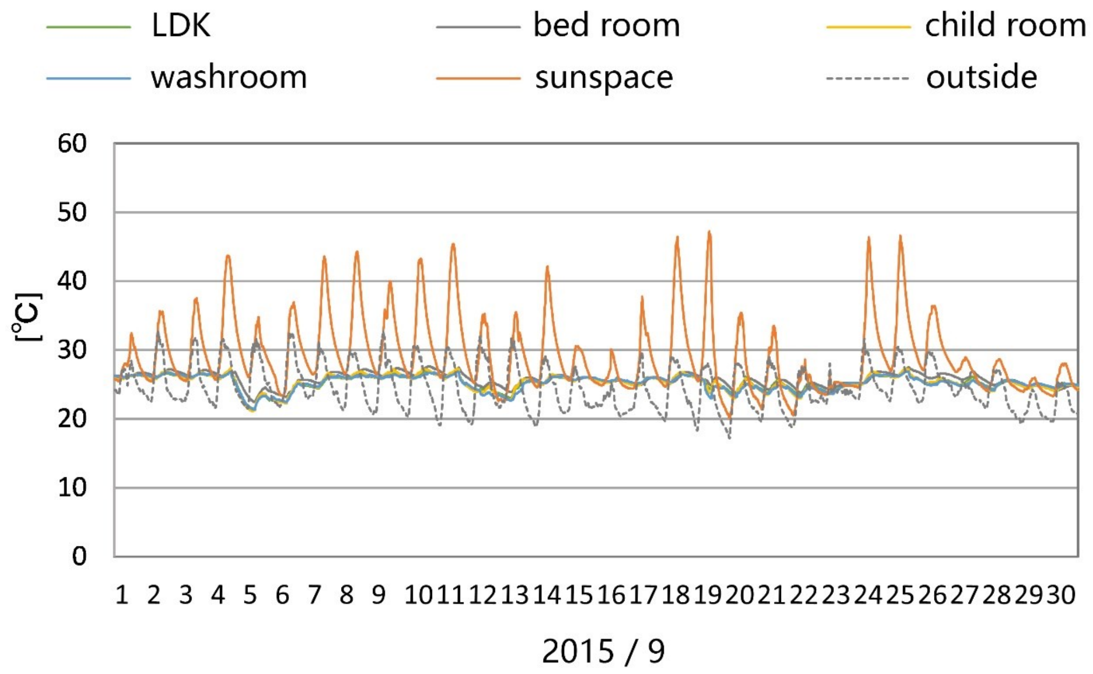

Figure 4.17 Each room temperature and outdoor air temperature (September)

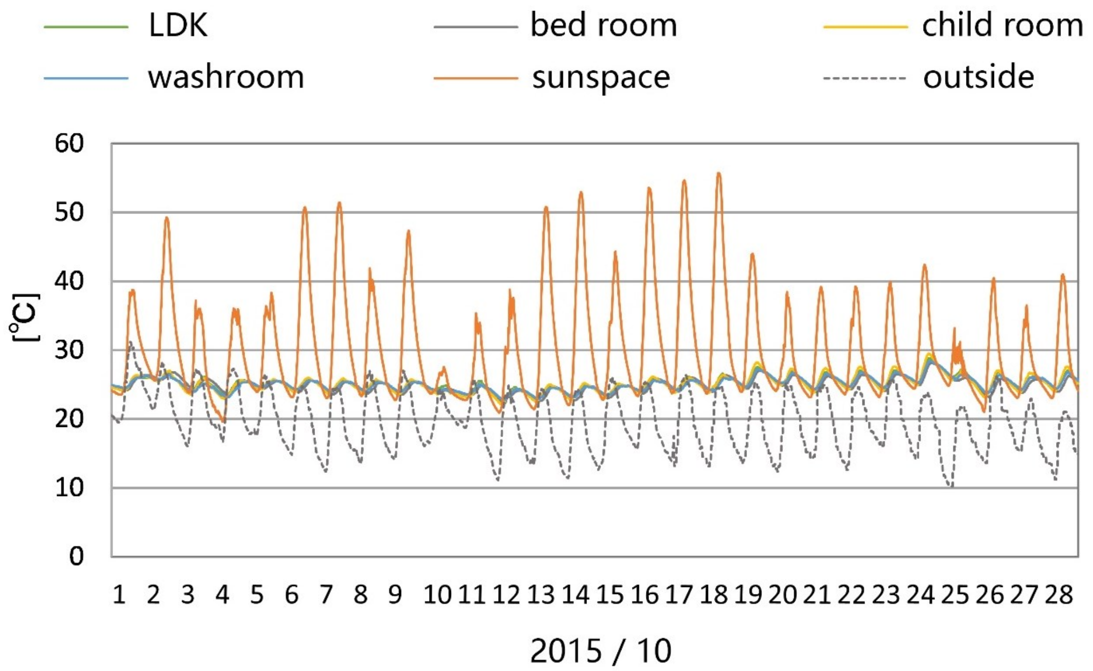

Figure 4.18 Each room temperature and outdoor air temperature (October)

Figures 4.19 and 4.20 show the temperature of each room, the temperature of the outside air, and solar radiation. In summer, the outer window of the sunspace is opened, so the outdoor air temperature and the sunspace temperature show similar values. On sunny days, the outdoor air temperature reaches around 35°C, while the temperature in each room is maintained at around 25°C. On sunny days, the temperature difference in each room is affected by solar radiation, but the temperature difference in each room on August 4 is 3.1°C. It can be concluded that the central air conditioning system has effectively improved indoor comfort. During the rainy days from July 4th to 5th, the outside temperature is declining, and the temperature in each room is rising. The air conditioner is in the dehumidification mode, and the temperature of each room is close to the air conditioning set temperature by dehumidifying the 20 °C humid air by heating.

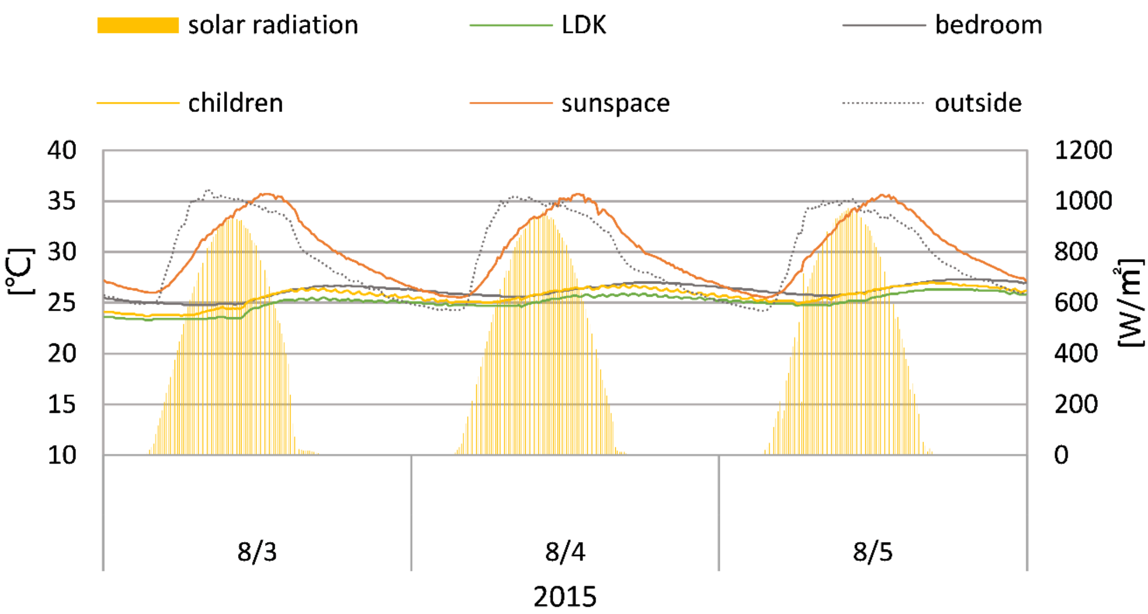

Figure 4.19 Each room and outdoor air temperature and solar radiation (3 sunny days in August)

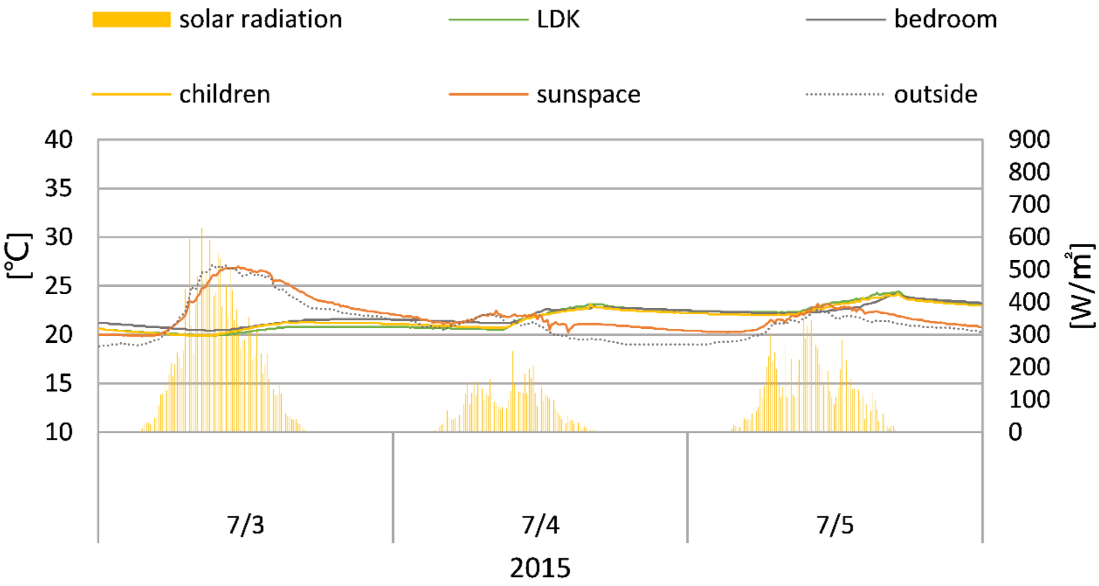

Figure 4.20 Each room and outdoor air temperature and solar radiation (3 rainy days in July)

4.3. Summary

A field study survey was conducted in this chapter to investigate the thermal performance of a sunspace attached to a house with a central air conditioning and air circulation system. The main conclusions are as follows:

(1) In winter, when the air conditioning temperature is set to 22 °C, the temperature of each room can be maintained at 20 °C by the central air conditioning even in the lowest outdoor air temperature. When the solar radiation is sufficient, the temperature inside the sunspace is 40 °C or higher, so we can confirm that sunspace is effective in collecting the heat. On sunny days, when the air in the sunspace is sent to the air conditioning room, the temperature in the sunspace drops slightly and the temperature is kept high. Therefore, it is necessary to consider ways to further use the heat inside the sunspace, such as adding additional thermal storage in the sunspace.

(2) In the intermediate period, the air conditioner was turned off, and the temperature of each room was maintained by sending the heat from the sunspace to the air conditioning room. In addition, in May, although the nighttime outdoor air temperature is lower than 20 °C, the air conditioning is turned off, and the air in the sunspace is not sent to the air conditioning room, but each room is at a comfortable temperature (22 °C ~ 28 °C). That's because the high insulation performance of the house can prevent the temperature from falling.

(3) In summer, each room is kept at a comfortable temperature (25 °C ~ 28 °C) by opening the outside window of the sunspace and turning on the air conditioning. Due to the high thermal insulation of the house, outdoor air has little effect on the indoor cooler air.

(4) During the day and night of the whole year, the temperature of each room will change with the change of outdoor air temperature and solar radiation and be kept at a comfortable temperature. In addition, due to the influence of solar radiation, there is a certain temperature difference between the north and south and the east and west rooms (± 3 °C). It can be concluded that the central air conditioning and air circulation system can adjust the comfort quickly and efficiently.

Chapter 5.

Effect of sending heat from the sunspace to the adjacent room

5. Effect of sending heat from the sunspace to the adjacent room

5.1. Introduction

Furthermore, the authors carried out measurement in a demonstration house in Miyazaki in winter from 2014 to 2015 to examine the impact of the passive heating method on the air-conditioning load reduction in a house with a central air conditioning and circulation system and reported that energy efficiency needs to be enhanced further. It is possible to supply air from a sunspace to adjacent rooms in the demonstration house, and there may be significant relations between a central air conditioning and circulation system and floor plan. The main purposes of this chapter are to identify heat collection effects and heating load reduction effects of a sunspace structure based on numerical simulation by examining efficient heat utilization methods within a sunspace and floor plans in winter.

5.2. All-day air conditioning

Heating loads and temperature were compared among Model I (a house with an attached sunspace on the second floor [equivalent to the demonstration house]), Model Io (a house with a window on the exterior of the sunspace opened to external air), and Model II (a house with the attached sunspace both on the first and second floors).

5.2.1. Computation conditions

Table 5.1 shows the computation conditions. Moving the air from a sunspace to the central HVAC (heating, ventilation, air conditioning system) machine room and taking the air from the sunspace to the adjacent rooms occurred only when the temperature within the sunspace was more than 24 degrees Celsius. The ventilation rates of the fan were controlled at 500 m^3/h and the central HVAC was on throughout the house all day. The air circulation between the central HVAC machine room and each room was 840 m^3/h for the living/ dining/kitchen (LDK) area, 560 m^3/h for the bedroom and the children's room, and 150 m^3/h for the other areas. Table 5.2 shows three different cases that were used for computation concerning air flow from the sunspace to the central HVAC machine room and air flow from the sunspace to adjacent rooms.

For Case 1, air flow from the sunspace to the central HVAC machine room on the second floor and air flow from the sunspace to the bedroom (Mode I and Model II) and living room (Model II) was performed. For Case 2, only air flow from the sunspace to the central HVAC machine room on the second floor was performed. For Case 3, air flow from the sunspace to the bedroom (Model I and Model II) and living room (Model II) was performed.

Table 5.1 Computation conditions

Computation area	Miyazaki city
Weather data	Expanded AMEDAS Weather Data (Miyazaki, reference year)
Computation period	November ~ April
Computation time interval	10 minutes
Heating method	Central HVAC, all-day heating
Heating set temperature	22 °C
Moisture and heat generation within a room	Nothing

Table 5.2 Cases

Case	Air flow from the sunspace to the central HVAC machine room	Air flow from the sunspace to the adjacent rooms
Case 1	Yes	Yes
Case 2	Yes	No
Case 3	No	Yes

5.2.2. Results and discussion

5.2.2.1. Heating load reduction effect by the attached sunspace

Figure 5.1 shows the annual heating loads of models I and II. In all three cases, compared to the heating load reduction effect of Model Io (opening the window on the exterior side of the sunspace), Model II (first- and second-floor sunspace) has a larger effect than Model I (first-floor sunspace). These results indicate the larger capacity of the sunspace structure had a greater heating load reduction effect. For models I and II, heating loads of Case 2 were smaller than for the other cases. This means air flow to the central HVAC machine room had a better heating load reduction effect than air flow from the sunspace structure to adjacent rooms. Compared to the Model Io, Model I could save about 15.6% of energy in Case 1, about 16.3% in Case 2, and about 8.6% in Case 3. The difference between Case 1 and Case 2 was small; therefore when the sunspace was only on the second floor, the air flow from the sunspace to the adjacent room did not affect the heating load. Compared to the Model Io, Model II could save about 29.9% of energy in Case 1, about 33.9% in Case 2, and about 18.5% in Case 3.

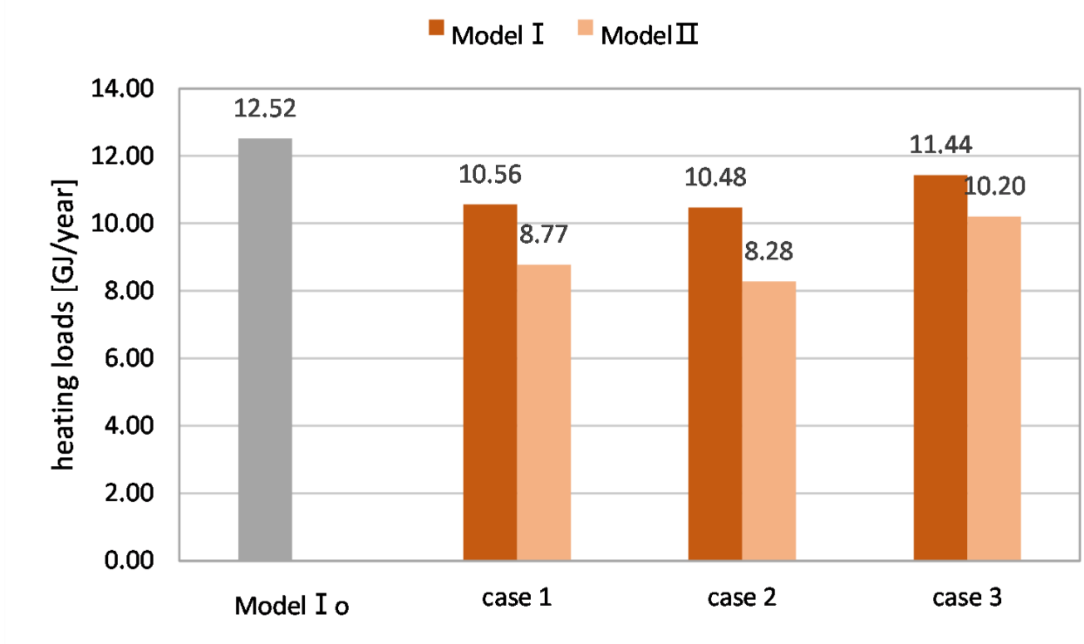

Figure 5.1 The annual heating loads of Model Io, Model I and Model II

5.2.2.2. Room temperature associated with air movement within the sunspace

Figure 5.2 shows the temperature within the attached sunspace. For all cases, the temperature of the sunspace was higher in Model II than in Model I. Especially, in Case 2 of Model II, the time when the temperature exceeds 24 ^{0}C is greater than others. The set temperature to send the air from the sunspace to the HVAC machine room was 24 ^{0}C. This may be the main reason for the heating load reduction shown in Figure 5.1. There was almost no difference in the temperatures between models I and II for Case 3. This means that the capacity of the sunspace of Model I is large enough, if the air is only taken from the sunspace to the adjacent rooms.

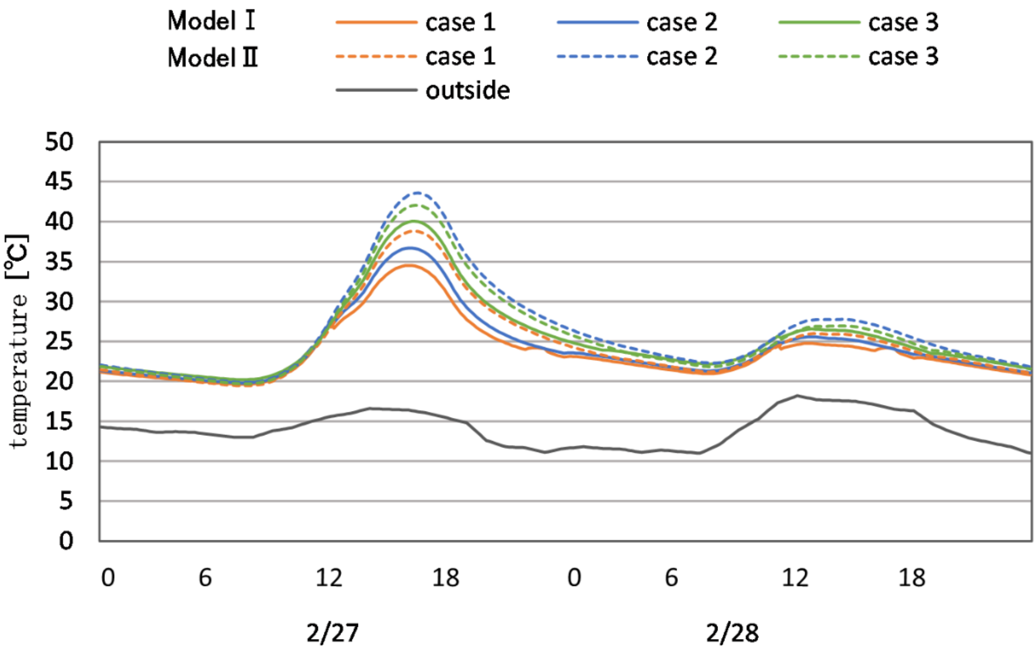

Figure 5.2 Temperature within the attached sunspace

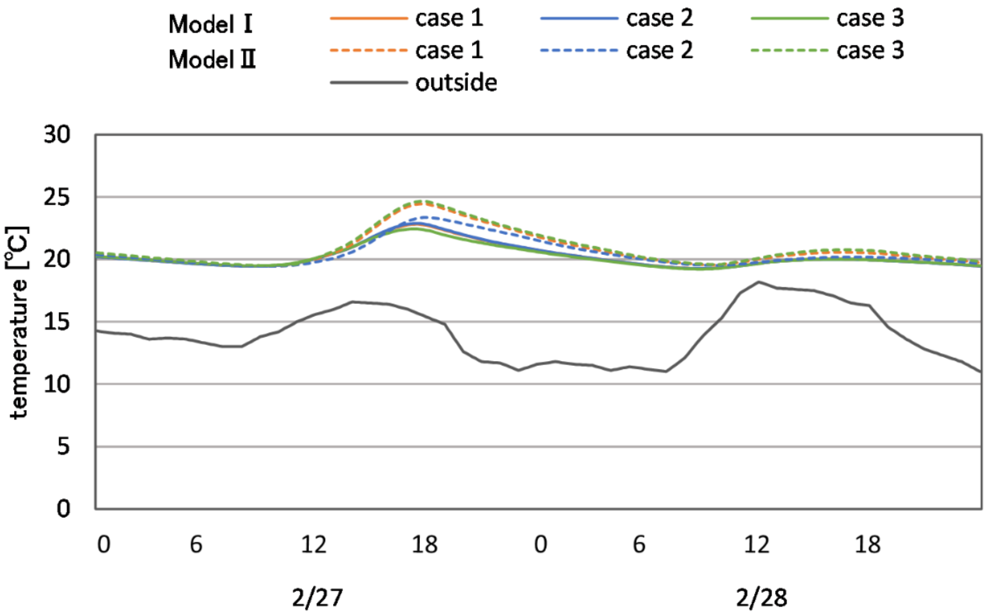

Figure 5.3 LDK (living/dining/kitchen) room temperature

Figure 5.3 shows the LDK (living/dining/kitchen) room temperature. Model II's temperature was always higher than Model I's in the LDK (living/dining/kitchen) room of Case 3. Because Model II's LDK (living /dining/kitchen) room was next to the sunspace structure, this result indicates that taking the air from the sunspace to the adjacent room contributed to the temperature increase in the LDK (living/dining/kitchen) room.

Figure 5.4 shows the bedroom temperature. The bedroom was adjacent to the sunspace structure for Model I and Model II. For Model I, the temperature of Case 3 changed at the highest level. This was probably because the entire air within the sunspace was used for the bedroom. For Model II, the temperature of Case 1 changed at the highest level.

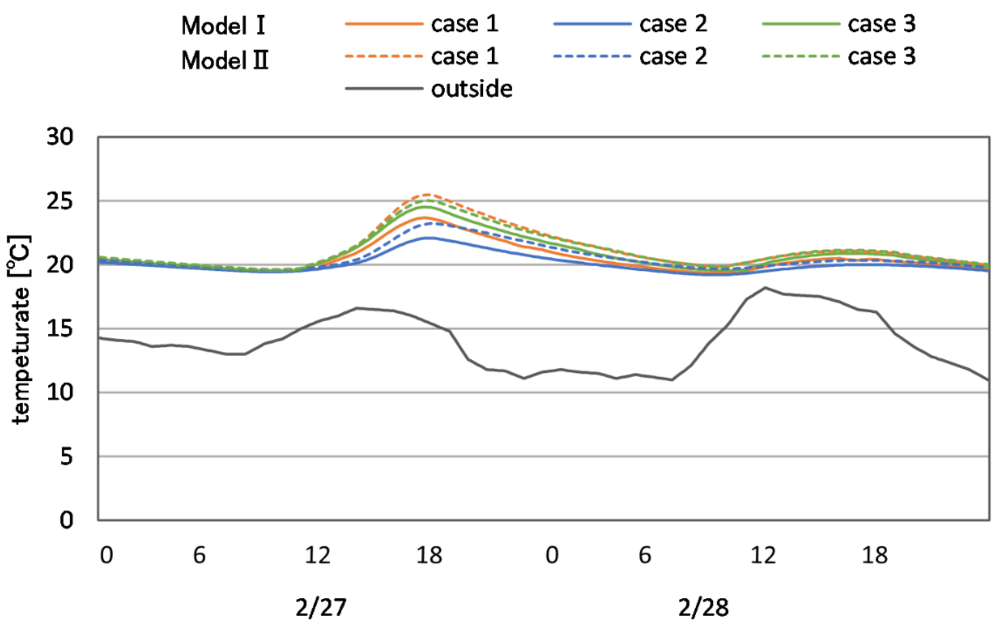

Figure 5.4 Bedroom temperature

Figures 5.5 and 5.6 show temperature in the central HVAC room and the child's room, respectively. For Case 2 of Models I and II, the temperature of the central HVAC room was high and, consequently, the air temperature sent from the HVAC room to the bedroom was high.

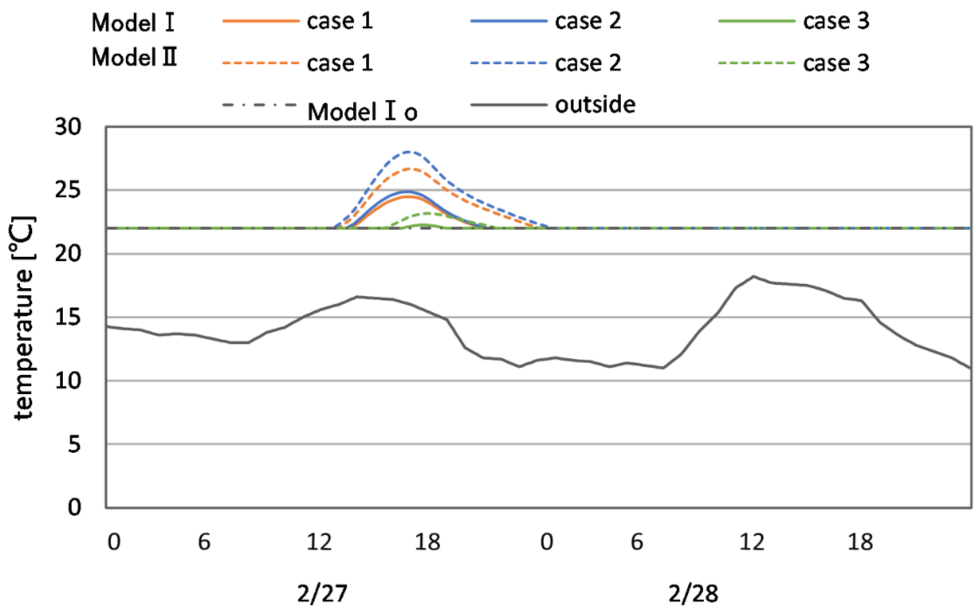

Figure 5.5 Temperature in the HVAC room

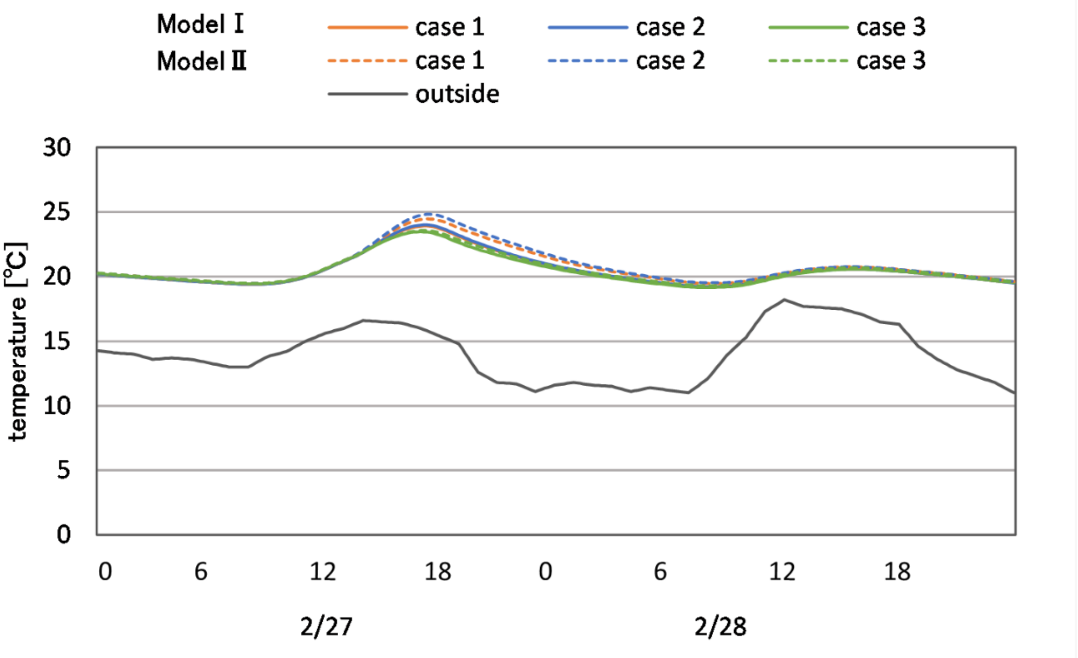

Figure 5.6 Children's room temperature

Figure 5.7 shows the temperature fluctuation of each room for Case 2 of Model II. On a sunny day, the temperature exceeded 40 ^{0}C in the sunspace. Sometimes, the temperature in the children's room was higher than that of the bedroom and the living room. This may have been caused by the heat transfer from the HVAC machine room, as the children's room was adjacent to the HVAC machine room.

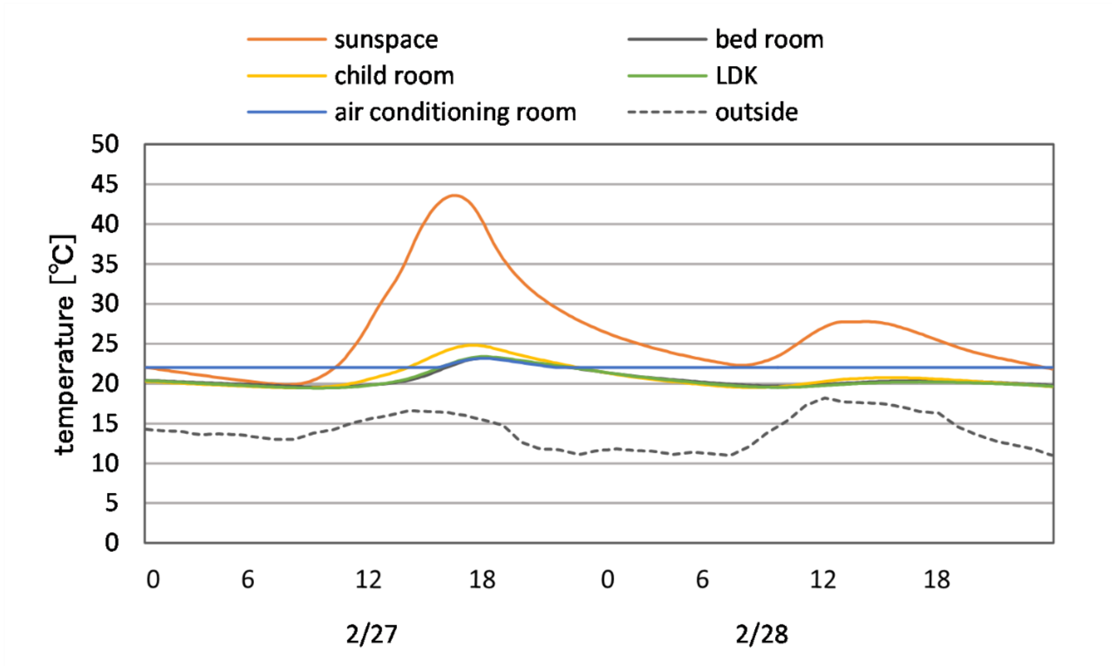

Figure 5.7 Temperature fluctuation of each room for Case 2 of Model II

5.3. Individual room air conditioning

Heating loads and temperature were compared between Model I (the bedroom is adjacent to the sunspace [equivalent to the demonstration house]) and Model I (the LDK is adjacent to the sunspace).

5.3.1. Computation conditions

Numerical simulations were performed in Case 1 and Case 2 of section 5.2.1. The air in the sunspace is sent to the adjacent room by opening the inside window of the sunspace only when someone is in the adjacent room. Table 5.3 shows the air conditioning condition, and Table 5.4 shows the calculation condition. There is a father (worker), a mother (housewife) and a child (student) in a family. There are two ways to use central HVAC system: all-day air conditioning and intermittent individual room air conditioning. The all-day air conditioning: The central HVAC system is on for 24 hours, and air is sent to each room from the central HVAC room. Intermittent individual room air conditioning: The central HVAC system is on only when people are at home, and air is sent to the room where people live from the central HVAC room. Only the necessary amount of ventilation (0.5 times/h) is sent to the room where no one lives. In January and February from the experimental study (refer to Chapter 4), the temperature in each room tended to be lower than the temperature set in the central HVAC room, so in January and February the air conditioning temperature was set to 24 °C and in other periods was set to 22 °C. The temperature of the adjacent room to the sunspace was set to 2 °C lower than the air conditioning set temperature.

Table 5.3 Air conditioning condition

All-day air conditioning	All rooms (central HVAC) Bedroom (an additional air conditioning) LDK (an additional air conditioning)
Intermittent individual room air conditioning	All rooms (central HVAC) Bedroom (an additional air conditioning) LDK (an additional air conditioning)

Table 5.4 Calculation condition

Computation area		Miyazaki city
Weather data		Expanded AMEDAS Weather Data (Miyazaki, reference year)
Family members		Father (worker), mother (housewife), child (student)
Schedule		Refer to chapter 2
Computation period		November to April
Computation time interval		10 minutes
Air conditioning set temperature	Central HVAC room	24°C (January and February) 22°C (November, December, March and April)
	Adjacent rooms of sunspace	22°C (January and February) 20°C (November, December, March and April)
Moisture and heat generation within rooms (bedroom and LDK)		Refer to chapter 2

5.3.2. Results and discussion

5.3.2.1. Heating load reduction and thermal environment (All-day air conditioning)

Figure 5.8 shows the annual heating load of all rooms (central HVAC), bedroom (an additional air conditioning) and LDK (an additional air conditioning) in all-day air conditioning. Figure 5.9 shows the temperature fluctuation of each room in all-day air conditioning (all rooms [central HVAC air conditioning]). Figure 5.10 shows the temperature fluctuation of each room in all-day air conditioning (bedroom [an additional air conditioning]). Figure 5.11 shows the temperature fluctuation of each room in all-day air conditioning (LDK [an additional air conditioning]).

The annual heating load increased by 0.5 GJ in the case of bedroom (an additional air conditioning) and 0.47 GJ in the case of LDK (an additional air conditioning). The annual heating load increased with an additional air conditioner. However, this is achieved by sending the heat from the sunspace to the adjacent room to reduce the annual load to 13.55 GJ and 13.49 GJ.

In the case of rooms (central HVAC), the bedroom temperature is sometimes lower than 20 °C (Figure 5.9). In other cases, the bedroom temperature is always above 20 °C (Figures 5.10 and 5.11).The annual heating load of bedroom (an additional air conditioning) is 0.06 GJ greater than the annual heating load of LDK (an additional air conditioning). It can be said that during the high temperature of the sunspace, the heating load can be reduced by using the adjacent room. Therefore, it is advisable for housewives to use LDK (adjacent to sunspace) for a long time during the daytime.

Figure 5.12 shows the temperature fluctuation of sunspace in all-day air conditioning. The sunspace temperature in the case of LDK (an additional air conditioning) was lower than cases all rooms (central HVAC) and bedroom (an additional air conditioning). It is advisable to design the room where the resident lives for a long time in the daytime beside the sunspace.

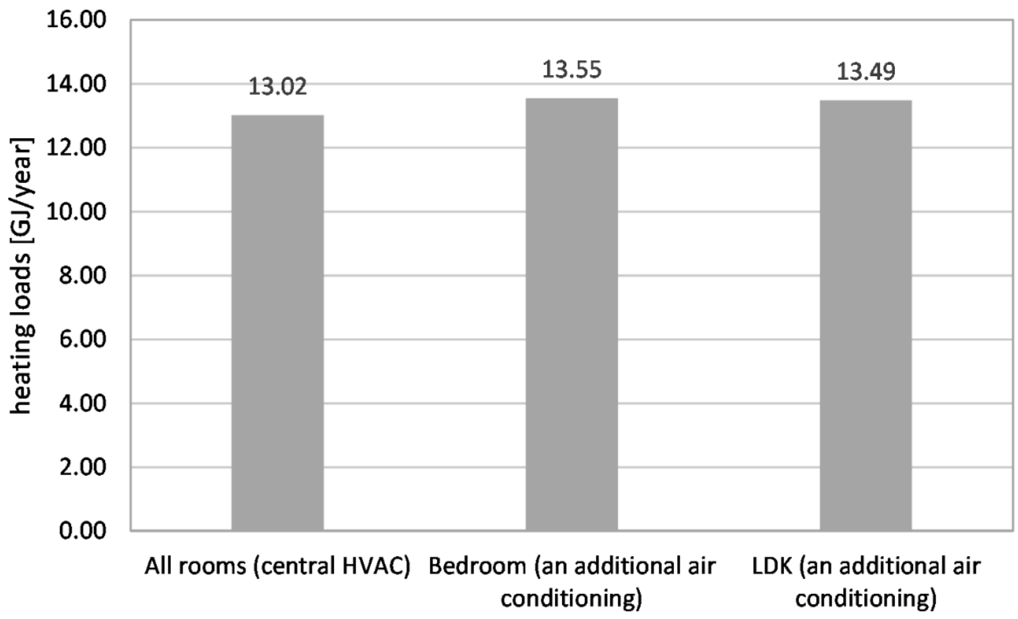

Figure 5.8 Annual heating load (all-day air conditioning)

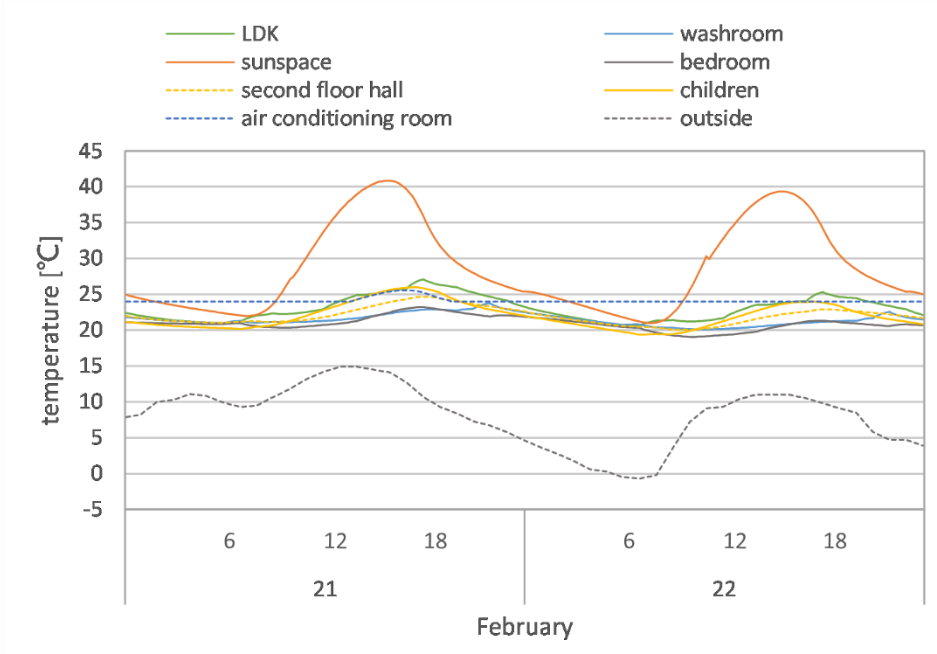

Figure 5.9 The temperature fluctuation of each room in all-day air conditioning (all rooms [central HVAC air conditioning])

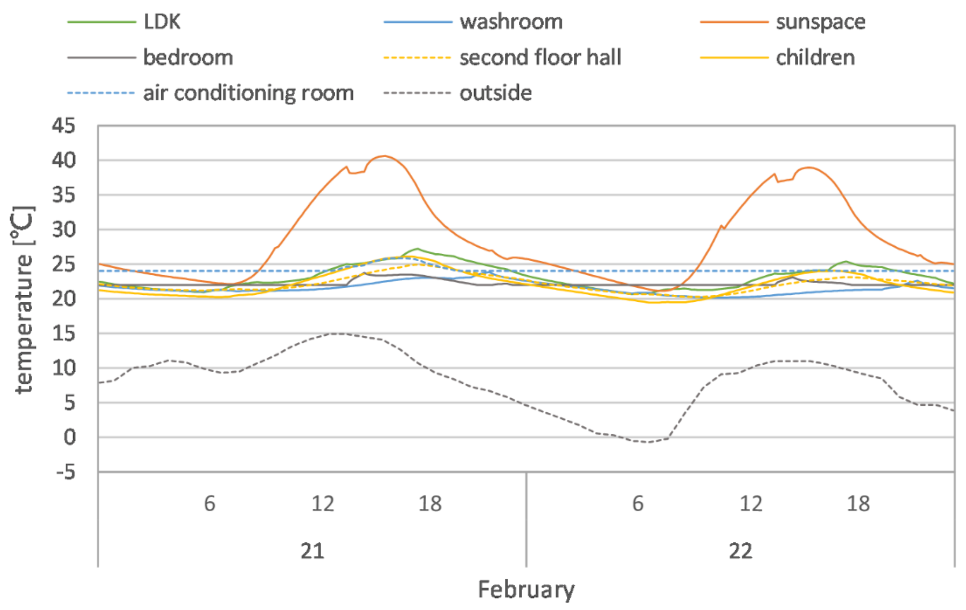

Figure 5.10 The temperature fluctuation of each room in all-day air conditioning (bedroom [an additional air conditioning])

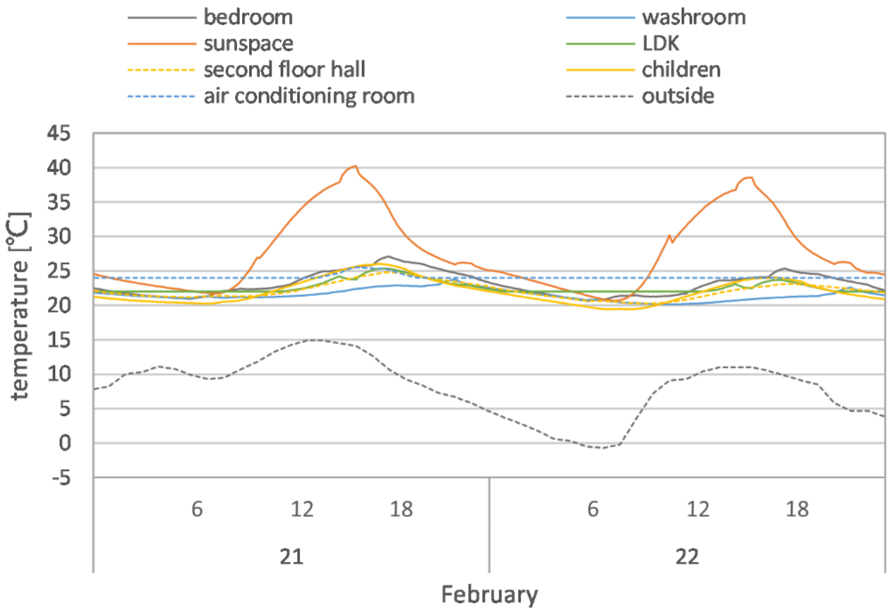

Figure 5.11 The temperature fluctuation of each room in all-day air conditioning (LDK [an additional air conditioning])

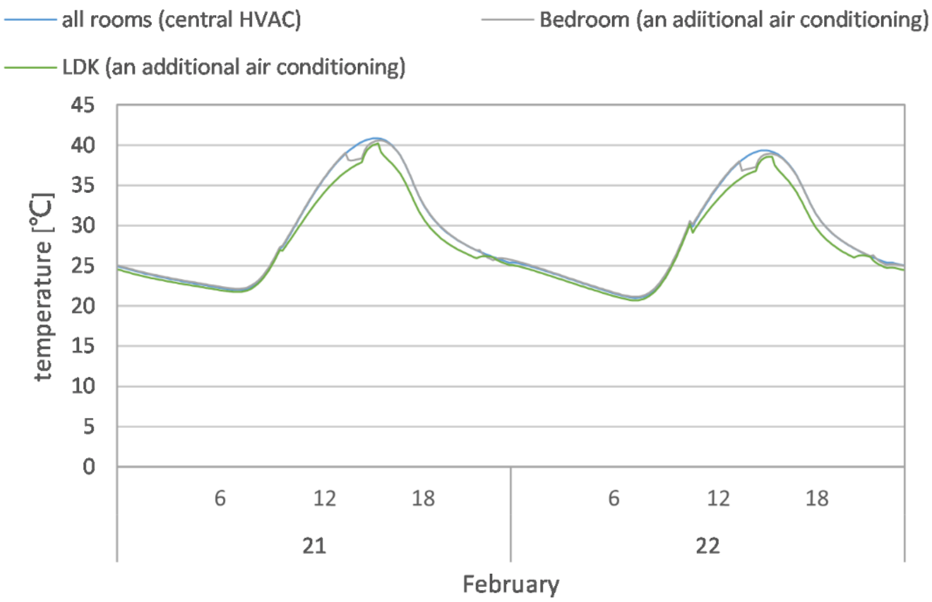

Figure 5.12 The temperature fluctuation of sunspace (all-day air conditioning)

5.3.2.2. Heating load reduction and thermal environment (intermittent individual room air conditioning)

Figure 5.13 shows the annual heating load of all rooms (central HVAC), bedroom (an additional air conditioning) and LDK (an additional air conditioning) in intermittent individual room air conditioning. Figure 5.14 shows the temperature fluctuation of each room in intermittent individual room air conditioning (all rooms [central HVAC air conditioning]). Figure 5.15 shows the temperature fluctuation of each room in intermittent individual room air conditioning (bedroom [an additional air conditioning]). Figure 5.16 shows the temperature fluctuation of each room in intermittent individual room air conditioning (LDK [an additional air conditioning]).

The annual heating load of all rooms (central HVAC), bedroom (an additional air conditioning) and LDK (an additional air conditioning) was 4.51 GJ, 5.70 GJ and 5.06 GJ, respectively. The annual heating load increased with an additional air conditioner. The annual heating load increased by 1.18 GJ in the case of bedroom (an additional air conditioning) and 0.54 GJ in the case of LDK (an additional air conditioning). However, this is achieved by sending the heat from the sunspace to the adjacent room to reduce the annual load to 13.55 GJ and 13.49 GJ.

The annual heating load of bedroom (an additional air conditioning) is 0.64 GJ greater than the annual heating load of LDK (an additional air conditioning). It can be said that during the high temperature of the sunspace, the heating load can be reduced by using the adjacent room. Therefore, it is advisable for housewives to use LDK (adjacent to sunspace) for a long time during the daytime.

Intermittent individual room air conditioning: The central HVAC system is on only when people are at home, and air is sent to the room where people live from the central HVAC room. Only the necessary amount of ventilation (0.5 times/h) is sent to the room where no one lives. In the case of rooms (central HVAC), the bedroom temperature falls below 20 ° C in many hours from 22:00 to 7:00, which is the time zone when the bedroom is used (Figure 5.14). In other cases, the bedroom temperature is always above 20 °C (Figures 5.10 and 5.11).

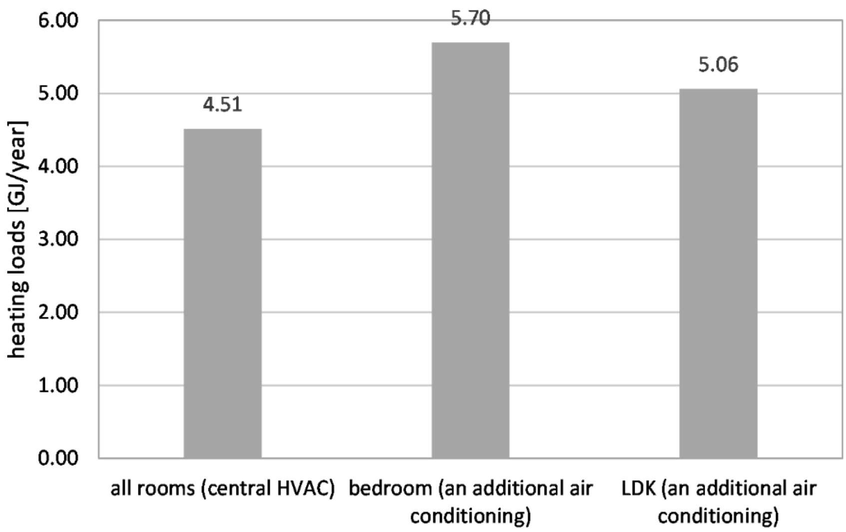

Figure 5.13 Annual heating load (intermittent individual room air conditioning)

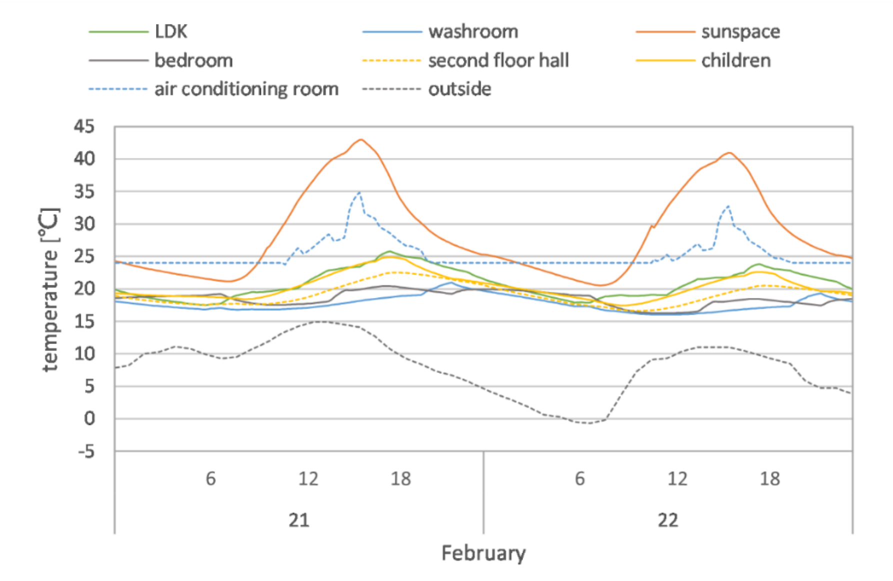

Figure 5.14 The temperature fluctuation of each room in intermittent air conditioning (all rooms air conditioning)

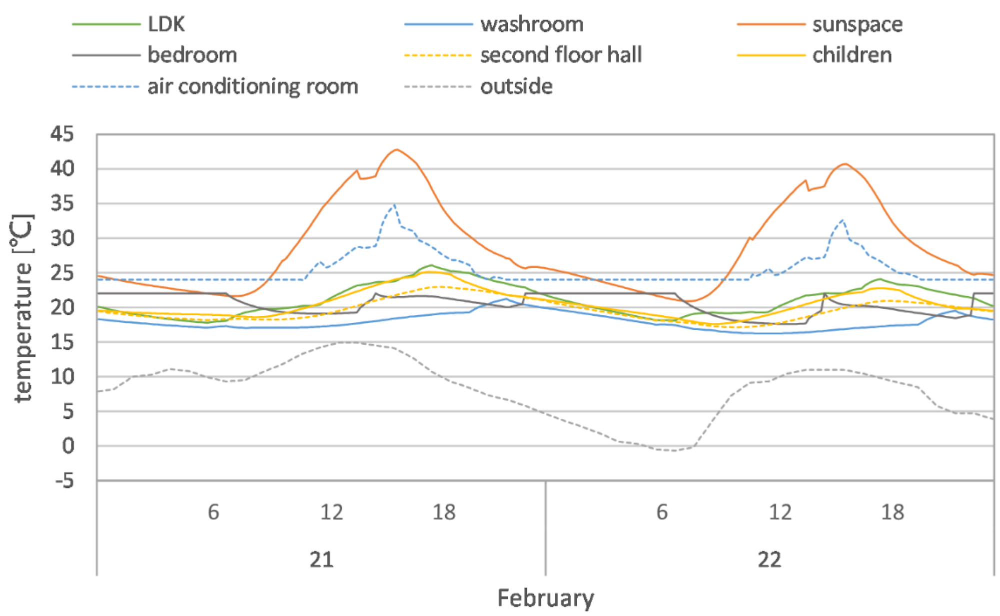

Figure 5.15 The temperature fluctuation of each room in intermittent individual room air conditioning (bedroom [individual air conditioning])

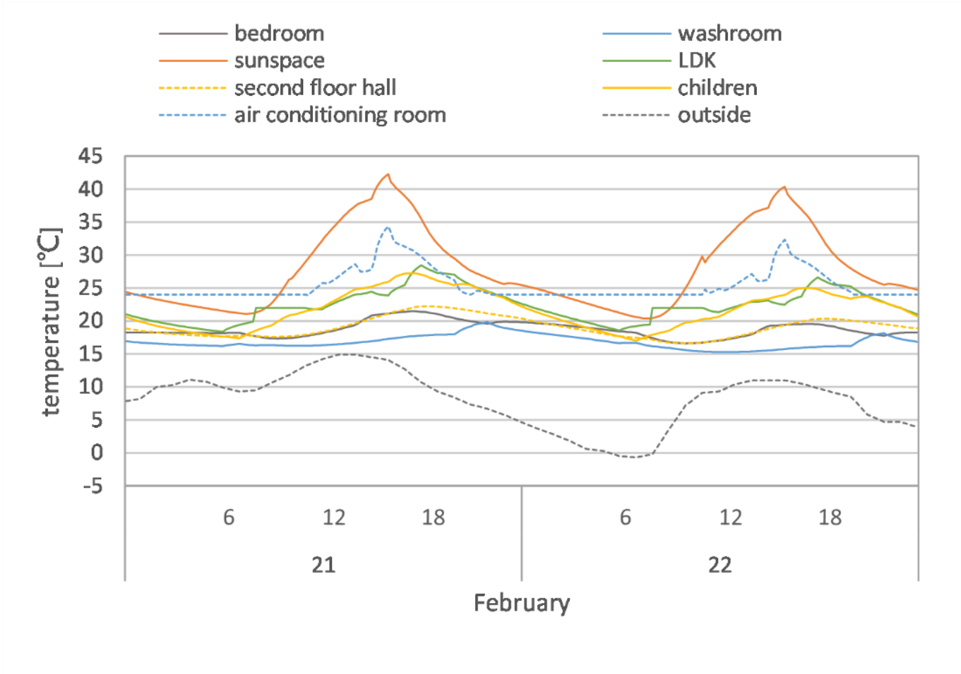

Figure 5.16 The temperature fluctuation of each room in intermittent individual room air conditioning (LDK [individual air conditioning])

Figure 5.17 shows the temperature fluctuation of sunspace in intermittent individual air conditioning. The sunspace temperature in the case of LDK (an additional air conditioning) was lower than cases all rooms (central HVAC) and bedroom (an additional air conditioning). It is advisable to design the room where the resident lives for a long time in the daytime beside the sunspace.

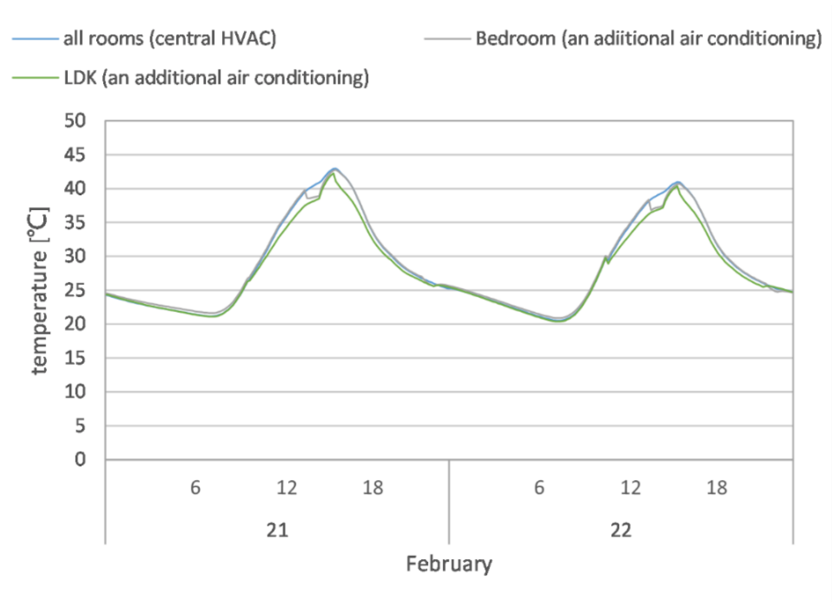

Figure 5.17 The temperature fluctuation of sunspace (intermittent individual room air conditioning)

5.4. Summary

In this chapter, the authors studied the heating load reduction effect using heat from the sunspace (the heat was sent to central HVAC room and adjacent room) and the temperature fluctuation of each room at the time of using heat from the sunspace.

For the case of the all-day central HVAC system, it was confirmed that the larger capacity of the sunspace structure, and not sending air from the sunspace space to the adjacent room, demonstrated a better heating load reduction effect.

Compared to the house without the sunspace (Model Io), the house with the sunspace on the second floor (Model I) could save about 15.6% of energy in Case 1 (air flow from the sunspace to the central HVAC machine room), about 16.3% in Case 2 (air flow from the sunspace to the central HVAC machine room and adjacent room), and about 8.6% in Case 3 (air flow from the sunspace to the adjacent room). The difference between Case 1 and Case 2 was small. Compared to the Model Io, The house with the sunspace on the first and second floors (Model II) could save about 29.9% of energy in Case 1, about 33.9% in Case 2, and about 18.5% in Case 3.

Sending heat from the sunspace space to the adjacent room led to a temperature increase in the adjacent room. However, if the construction plan is to have a sunspace structure only on the second floor, the house should be carefully designed, for example, by placing a living room on the second floor.

The annual heating load increased with an additional air conditioner. During the high temperature of the sunspace, the heating load can be reduced by using the adjacent room. It is advisable to design the room where the resident lives for a long time in the daytime beside the sunspace.

Chapter 6.

Performance comparison between a sunspace, double skin facade and Trombe wall

6. Performance comparison between a sunspace, double skin facade and Trombe wall

6.1. Introduction

With the promotion of highly insulated and sealed houses, the central air conditioning systems that integrate ventilation, cooling and heating have received attention. In addition, solar heat utilization is attracting attention as an effective means to reduce energy consumption of cooling/heating and hot water supply. Therefore, research and development of houses combining the central air conditioning system and solar energy utilization are necessary for a comfortable thermal environment and energy saving. In this chapter, numerical studies on the energy performance of the sunspace, DSF (double skin facade) and Trombe wall were carried out. THERB for HAM software was used to study the energy performance.

6.2. Calculation conditions

Table 6.1 shows the calculation conditions. There are two situations in a family: mother is a housewife and stays at home all day; mother is a worker and nobody stays at home during the day. Figure 6.1 shows the time schedule of father (worker), child (primary school), and mother (housewife/worker) at home. In January and February, the central air conditioning was set at 24°C and was set at 22°C in November, December, March and April. The air is sent to the central air conditioning room from the sunspace, DSF and Trombe wall only when the temperature inside the sunspace, DSF and Trombe wall is above 24°C. The air circulation between the sunspace, DSF and Trombe wall and central air conditioning room is 560 m^3/h. The air circulation between the each room and central air conditioning room is 840 m^3/h for the LDK (living/dining/kitchen), 560 m^3/h for the child's room and the bedroom, and 150 m^3/h for the others.

There are three ways to use central air conditioning: all-day air conditioning, intermittent air conditioning, and intermittent individual room air conditioning. The all-day air conditioning: The central air conditioning system is on for 24 hours, and air is sent to each room from the central air conditioning room. Intermittent air conditioning: The central air conditioning is on only when people are at home, and air is sent to each room from the central air conditioning room. In the absence of people, the central air conditioning is off and the air circulation only needs to meet the necessary ventilation (0.5 times/h). Intermittent individual room air conditioning: The central air conditioning is on only when people are at home, and air is sent to the room where people live from the central air conditioning room. Only the necessary amount of ventilation (0.5 times/h) is sent to the room where no one lives. In real life, if mother is a housewife, it may be all-day air conditioning and intermittent individual room air conditioning. If the mother is a worker, it may be intermittent air conditioning and intermittent individual room air conditioning.

Energy consumption was compared between Model Io (balcony on the second floor), Model I (sunspace on the second floor [the experiment house]), Model II (sunspace on the first and second floors), Model III (double skin facade on the second floor), Model IV (double skin facade on the first and second floors), Model V (Trombe wall on the second floor), and Model VI (Trombe wall on the first and second floors). The energy consumption of each Model is compared in four ways using air conditioning (all-day air conditioning, intermittent air conditioning, intermittent individual room air conditioning [mother is a worker], intermittent individual room air conditioning [mother is a housewife]).

Table 6.1 Calculation conditions

Computation area Weather data	Miyazaki city Expanded AMEDAS Weather Data (Miyazaki, reference year)
Family members	Father (worker), mother (housewife), child (student) Father (worker), mother (worker), child (student)
Schedule Computation period Computation time interval	Refer to chapter 2 November to April 10 minutes
Air conditioning method	All-day air conditioning Intermittent air conditioning Intermittent individual room air conditioning
Air conditioning set temperature	24°C (January and February) 22°C (November, December, March and April)
Moisture and heat generation within rooms (bedroom and LDK)	Refer to chapter 2

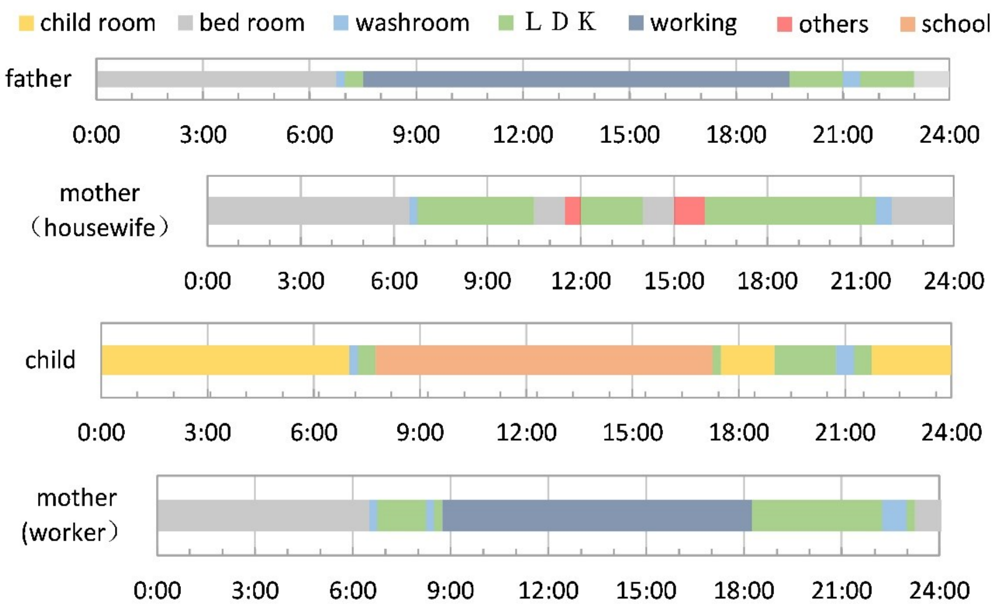

Figure 6.1 The time schedule of father, child, and mother (housewife/worker) at home

6.3. Simulation results (sunspace)

6.3.1. Annual heating load (sunspace)

Simulation studies were carried out in the case of all-day air conditioning, intermittent air conditioning, intermittent individual room air conditioning (mother is a worker), intermittent individual room air conditioning (mother is a housewife). The air is sent to the central air conditioning room from a sunspace only when the temperature inside the sunspace is above 24°C. The air circulation between the sunspace and central air conditioning room is 500 m^3/h. Figure 6.2 shows the annual heating load of Model Io, Model I, and Model II. In the case of all-day air conditioning, the annual heating loads of Model Io, Model I and Model II was 14.82 GJ, 13.02 GJ and 10.44 GJ, respectively. In the case of intermittent air conditioning, the annual heating loads of Model Io, Model I and Model II was 11.94 GJ, 10.72 GJ and 10.39 GJ, respectively. In the case of intermittent individual room air conditioning (housewife), the annual heating loads of Model Io, Model I and Model II was 5.60 GJ, 4.51 GJ and 3.63 GJ, respectively. In the case of intermittent individual room air conditioning (worker), the annual heating loads of Model Io, Model I and Model II was 4.58 GJ, 3.96 GJ and 3.46 GJ, respectively. Due to there is no sunspace in Model Io, the Model Io has the largest annual heating load. The heating load of Model II is less than the Model I because Model II has a large sunspace than the Model I. The increase of the space for heat collection prolongs the period of high temperature of the sunspace, resulting in an increase in the temperature of the sunspace.

In Models Io, I and II, the case of all-day air conditioning consumed the most energy. The case of intermittent individual room air conditioning (worker) used the least energy. The case of intermittent individual room air conditioning (housewife) consumed more energy than the case of intermittent individual room air conditioning (worker), but there is not much difference between them. In Model Io, the cases of the intermittent air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 2.88 GJ, 9.22 GJ, and 10.87 GJ, respectively, compared to all-day air conditioning. In Model I, the cases of the intermittent air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 2.3 GJ, 8.5 GJ, and 9.05 GJ, respectively, compared to all-day air conditioning. In Model II, the cases of the intermittent air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 0.05 GJ, 6.81 GJ, and 6.98 GJ, respectively, compared to all-day air conditioning.

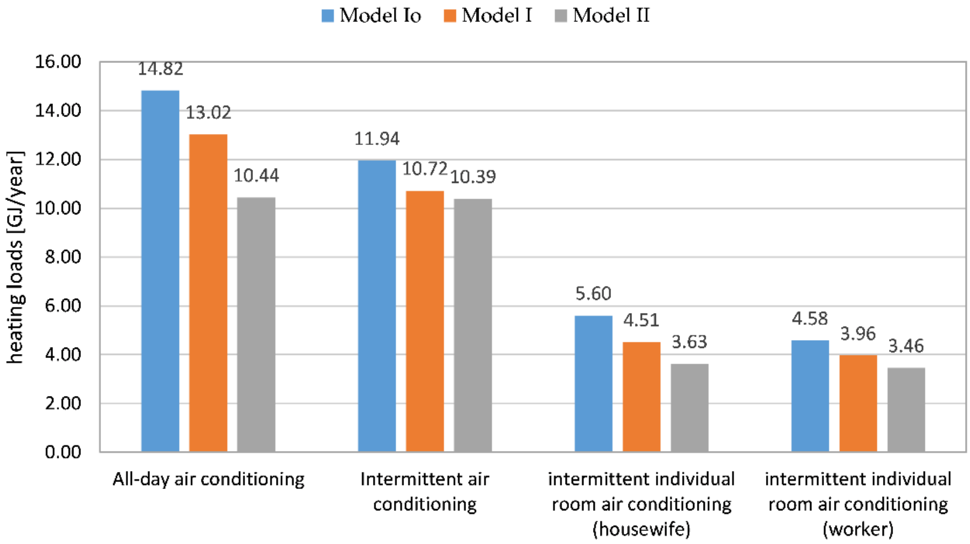

Figure 6.2 Annual heating load of Model Io, Model I, and Model II

6.3.2. Monthly heating load (sunspace)

Table 6.2 shows the basic meteorological parameters of Miyazaki. Figure 6.3, Figure 6.4 and Figure 6.5 show the monthly heating load of model Io, model I and model II, respectively. The heating load in January is the largest in three Models with different air conditioning methods. Since the average temperature in January was the lowest, it was considered that the heating load was affected by the outside air temperature. In the Model Io with different air conditioning methods, the heating load decreases as the outside air temperature increases. That's because the model Io has no sunspace, so the heating load changes with the outside air temperature.

When the outdoor air temperature is high (April and November), the heating load difference between intermittent individual room air conditioning (housewife) and intermittent individual room air conditioning (worker), and the heating load difference between all-day air conditioning and intermittent air conditioning is small. When the outdoor air temperature is high (April and November), the heating load difference between all-day air conditioning and intermittent individual room air conditioning (worker) is small. When the outdoor air temperature is low (January, February, and March), there is a large difference in the heating load between all-day air conditioning and intermittent individual room air conditioning (worker). The heating load difference between intermittent individual room air conditioning (housewife) and intermittent individual room air conditioning (worker), and the heating load difference between all-day air conditioning and intermittent air conditioning were smallest in Model II and largest in Model Io. It can be said that the heating load reduction effect by air circulation between the sunspace and the central air conditioning room is large in the month of low outside air temperature. It can be said that in the months when the outside air temperature is low, the air circulation between the central air conditioning room and the air cavity of sunspace greatly reduced the heating load. In January, the heating load reduction rate of intermittent air conditioning was small, and the reduction rate of all-day air conditioning was large. And the heating load reduction rate of intermittent individual room air conditioning (worker) was small, and the reduction rate of intermittent individual room air conditioning (housewife) was large. In November, December, and April, the heating load of the all-day air conditioning of Model II was lower than that of the intermittent air conditioning. It can be concluded that if there is a house with a large volume of sunspace (Model II), it is best to use central air conditioning all day when the outside air temperature is high.

Table 6.2 Some meteorological parameters of Miyazaki

Miyazaki	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Temperature [°C]	13.7	9.5	7.7	8.2	11.6	16.7
Global solar irradiation [MJ/m^2]	348.6	296	307.5	339.2	424.2	436.1
Wind velocity [m/s]	1.8	2.1	1.9	2.3	2.3	2.2
Humidity ratio [g/kg’]	7	5.2	4.3	4.9	6.1	8.3

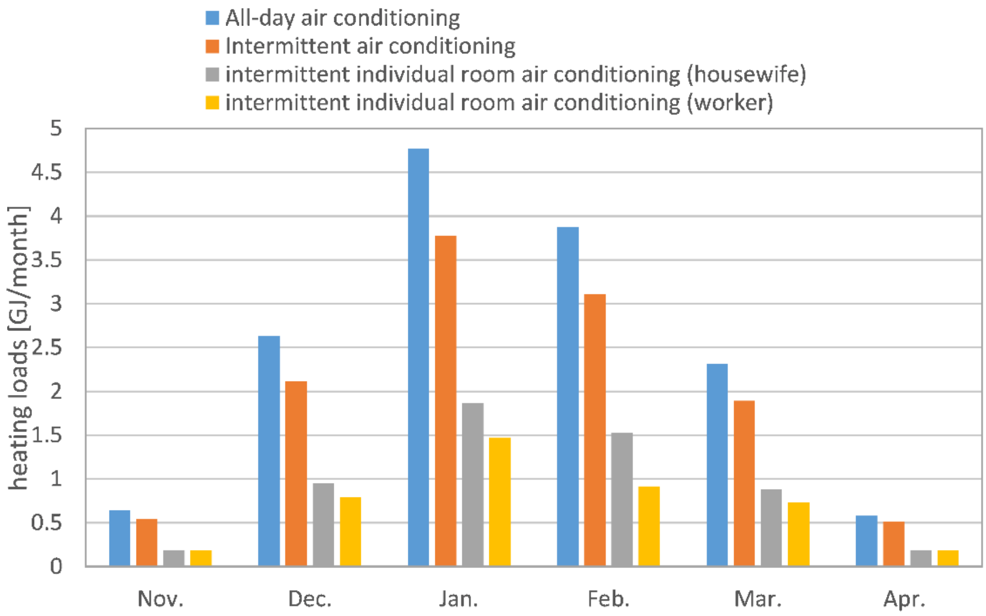

Figure 6.3 Monthly heating load of Model Io

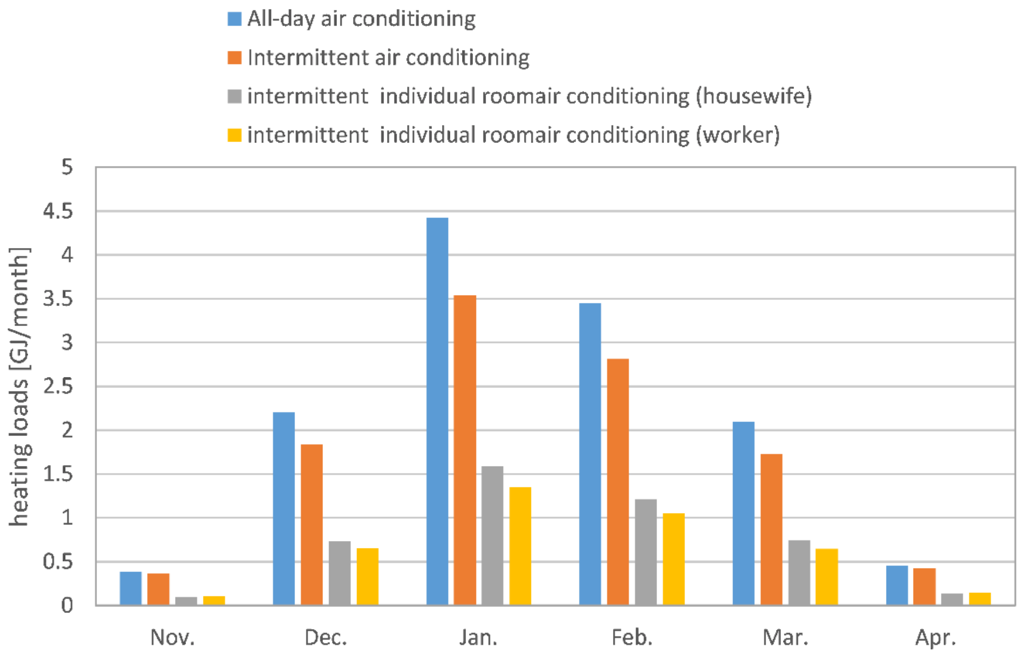

Figure 6.4 Monthly heating load of Model I

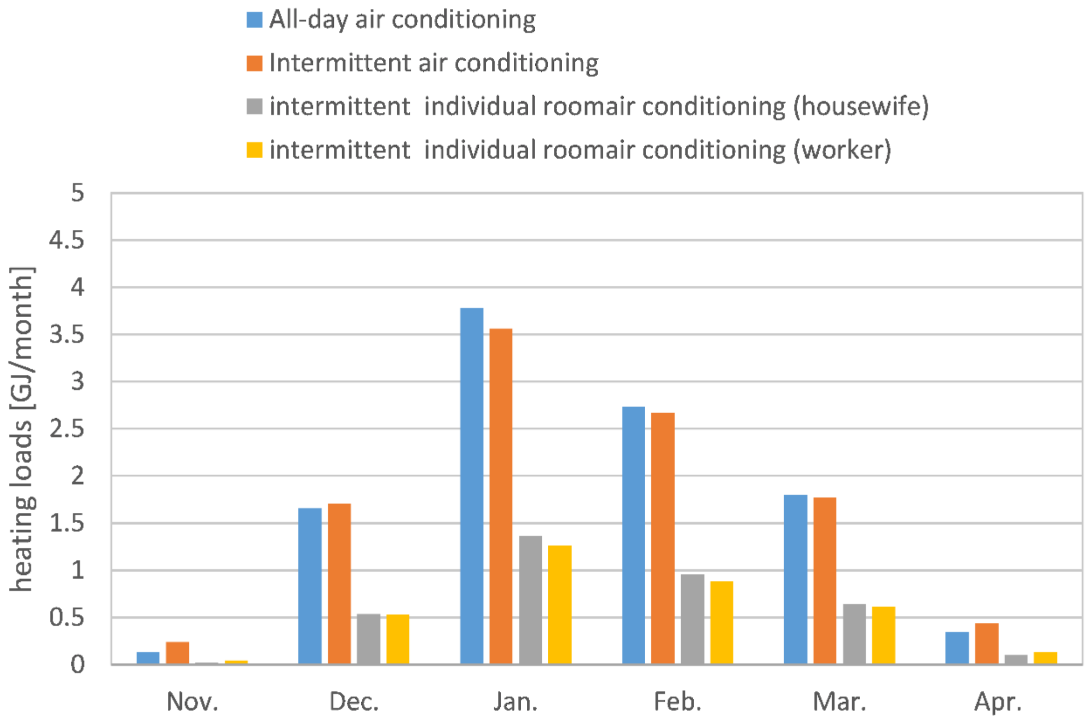

Figure 6.5 Monthly heating load of Model II

6.3.3. The heating load varies with time (sunspace)

Figures 6.6, 6.7 and 6.8 show the heating load of Model Io, model I and model II over time on two sunny days, respectively. In all Models with intermittent air conditioning or intermittent individual room air conditioning (worker or housewife), the heating load increased when the central air conditioning system is used again after the air conditioning system is stopped. It can be concluded that when the central air conditioning system is turned off, the temperature of the central air conditioning room decreases, and when the central air conditioning system is turned on again, a large amount of energy is required to reach the central air conditioning setting temperature.

In the Models Io, I and II, the heating load of the intermittent air conditioning is larger than the all-day air conditioning during the period of when the intermittent air conditioning is used. However, the all-day air conditioning uses a large heating load during the period of when the intermittent air conditioning is stopped. Therefore, it can be said that the intermittent air conditioning can reduce the annual heating load compared with the all-day air conditioning (Figure 6.2). In the case of all-day air conditioning, the heating load decreased from 9:00 to 16:00. Model II has the greatest reduction rate and Model Io had the lowest reduction rate. It can be said that the sunspace collect heat during the daytime to reduce energy consumption.

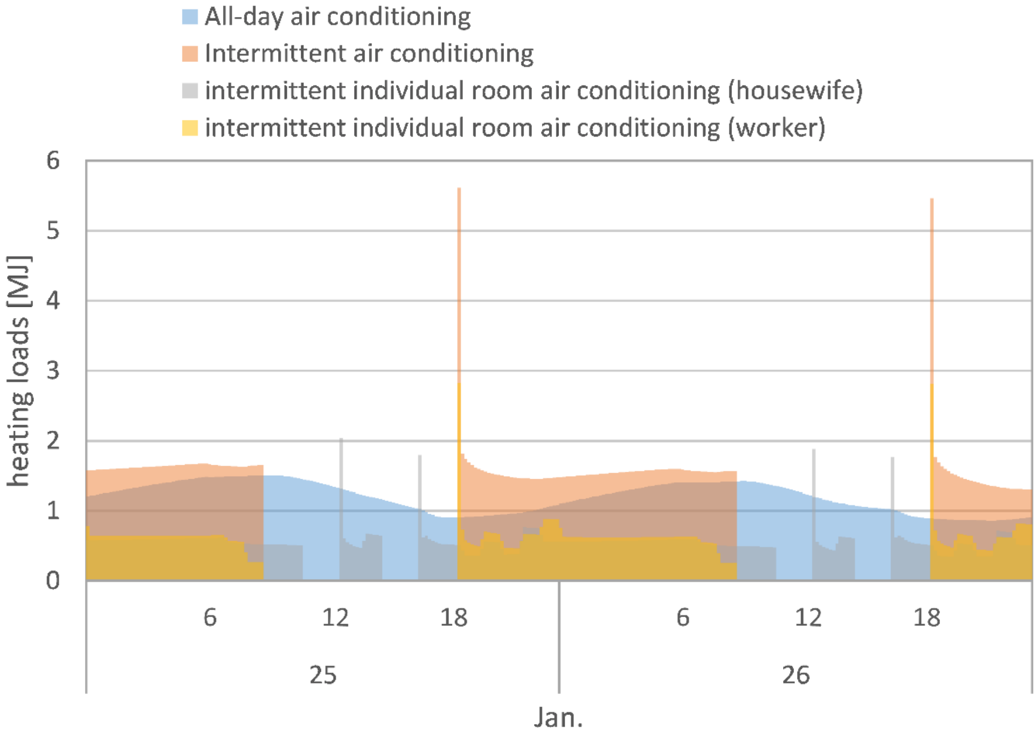

Figure 6.6 The heating load varies with time (Model Io)

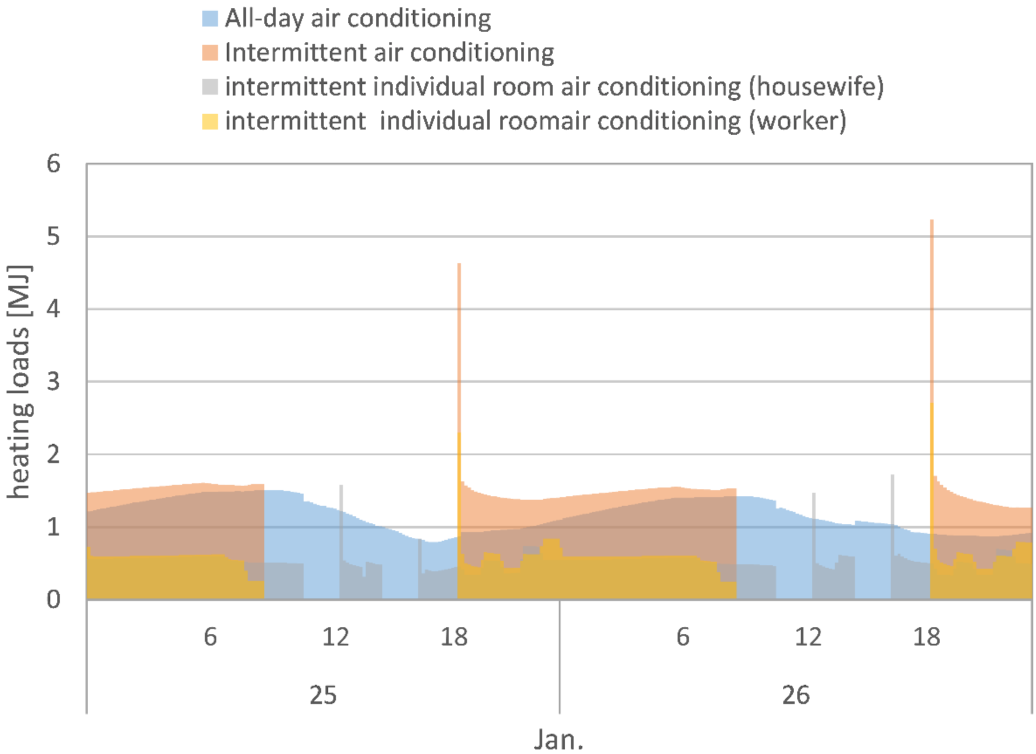

Figure 6.7 The heating load varies with time (Model I)

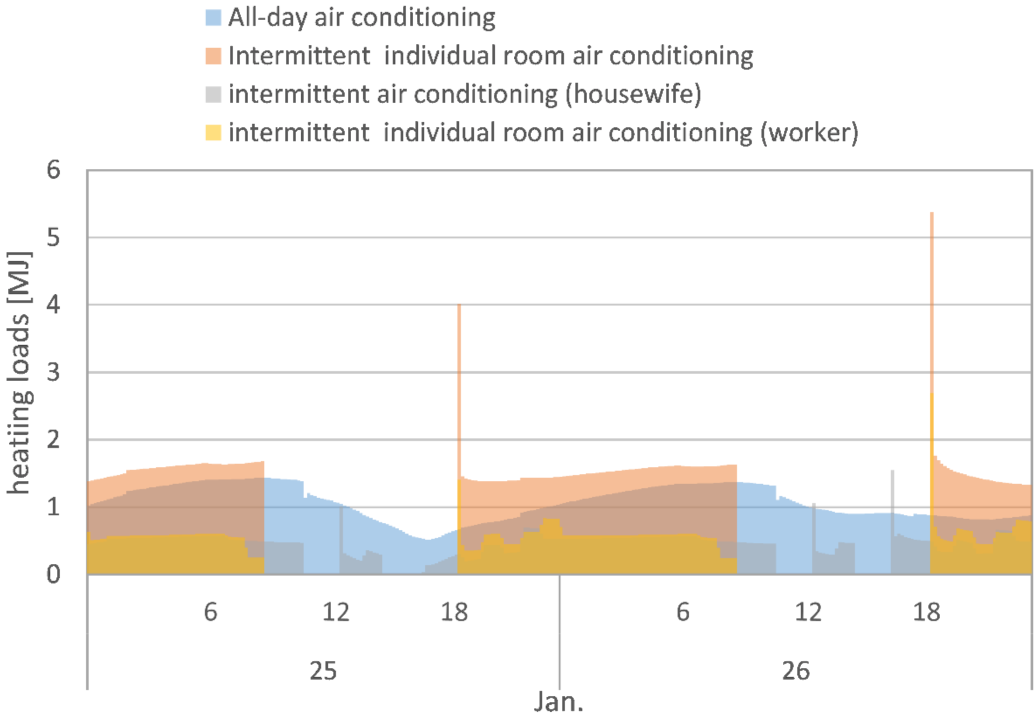

Figure 6.8 The heating load varies with time (Model II)

6.4. Simulation results (double skin facade)

6.4.1. Annual heating load (double skin facade)

Simulation studies were carried out in the case of all-day air conditioning, intermittent air conditioning, intermittent individual room air conditioning (mother is a worker), intermittent individual room air conditioning (mother is a housewife). The air is sent to the central air conditioning room from a double skin facade only when the temperature inside the sunspace is above 24°C. The air circulation between the double skin facade and central air conditioning room is 500 m^3/h. Figure 6.9 shows the annual heating load of Model Io, Model III, and Model IV. In the case of all-day air conditioning, the annual heating loads of Model Io, Model III and Model IV was 14.82 GJ, 12.83 GJ and 9.95 GJ, respectively. In the case of intermittent air conditioning, the annual heating loads of Model Io, Model III and Model IV was 11.94 GJ, 10.56 GJ and 9.84 GJ, respectively. In the case of intermittent individual room air conditioning (housewife), the annual heating loads of Model Io, Model III and Model IV was 5.60 GJ, 4.75 GJ and 3.87 GJ, respectively. In the case of intermittent individual room air conditioning (worker), the annual heating loads of Model Io, Model III and Model IV was 4.58 GJ, 3.92 GJ and 3.45 GJ, respectively. The heating load of Model IV is less than the Model III because Model IV has a large double skin facade than the Model III. The increase of the space for heat collection prolongs the period of high temperature of the double skin facade, resulting in an increase in the temperature of the double skin facade.

In Models Io, III and IV, the case of all-day air conditioning consumed the most energy. The case of intermittent individual room air conditioning (worker) used the least energy. The case of all-day air conditioning consumed more energy than the case of intermittent air conditioning, but there is not much difference between them. The case of intermittent individual room air conditioning (housewife) consumed more energy than the case of intermittent individual room air conditioning (worker), but there is not much difference between them. In Model III, the cases of the intermittent air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 2.27 GJ, 8.08 GJ, and 8.91 GJ, respectively, compared to all-day air conditioning. In Model IV, the cases of the intermittent air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 0.10 GJ, 6.08 GJ, and 6.50 GJ, respectively, compared to all-day air conditioning.

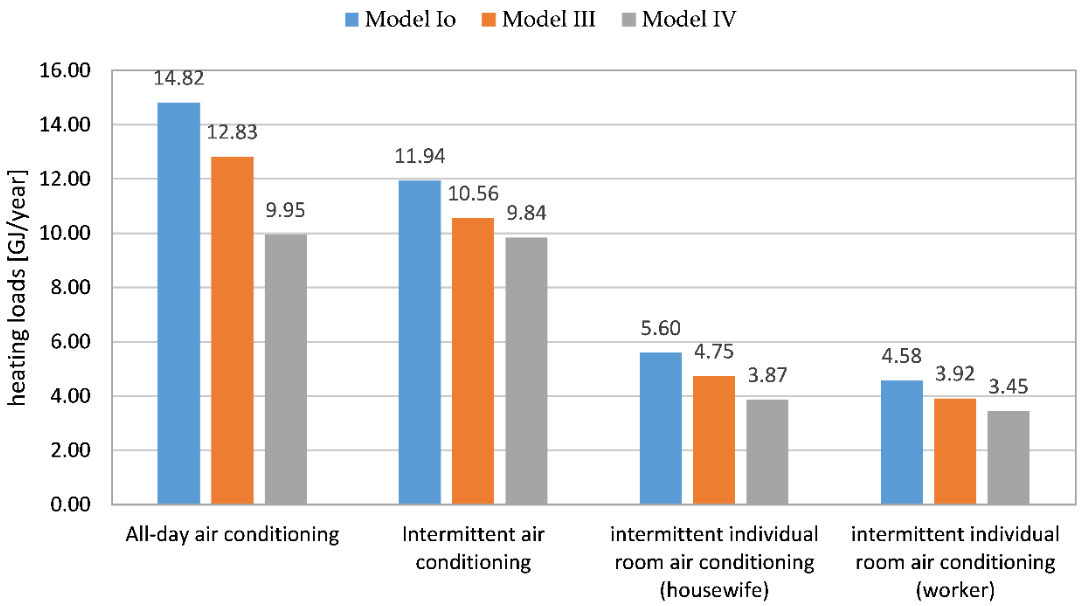

Figure 6.9 Annual heating load of Model Io, Model III, and Model IV

6.4.2. Monthly heating load (double skin facade)

Figure 6.10 and Figure 6.11 show the monthly heating load of model III and model IV, respectively. The heating load in January is the largest in two Models with different air conditioning methods. Since the average temperature in January was the lowest, it was considered that the heating load was affected by the outside air temperature.

When the outdoor air temperature is high (April and November), the heating load difference between intermittent individual room air conditioning (housewife) and intermittent individual room air conditioning (worker), and the heating load difference between all-day air conditioning and intermittent air conditioning is small. When the outdoor air temperature is high (April and November), the heating load difference between all-day air conditioning and intermittent individual room air conditioning (worker) is small. When the outdoor air temperature is low (January, February, and March), there is a large difference in the heating load between all-day air conditioning and intermittent individual room air conditioning (worker). The heating load difference between intermittent individual room air conditioning (housewife) and intermittent individual room air conditioning (worker), and the heating load difference between all-day air conditioning and intermittent air conditioning were smallest in Model IV and largest in Model Io. It can be said that the heating load reduction effect by air circulation between the double skin facade and the central air conditioning room is large in the month of low outside air temperature. It can be said that in the months when the outside air temperature is low, the air circulation between the central air conditioning room and the air cavity of double skin facade greatly reduced the heating load. In January, the heating load reduction rate of intermittent air conditioning was small, and the reduction rate of all-day air conditioning was large. And the heating load reduction rate of intermittent individual room air conditioning (worker) was small, and the reduction rate of intermittent individual room air conditioning (housewife) was large. In November, December, and April, the heating load of the all-day air conditioning of Model IV was lower than that of the intermittent air conditioning. It can be concluded that if there is a house with a large volume of double skin facade (Model IV), it is best to use central air conditioning all day when the outside air temperature is high.

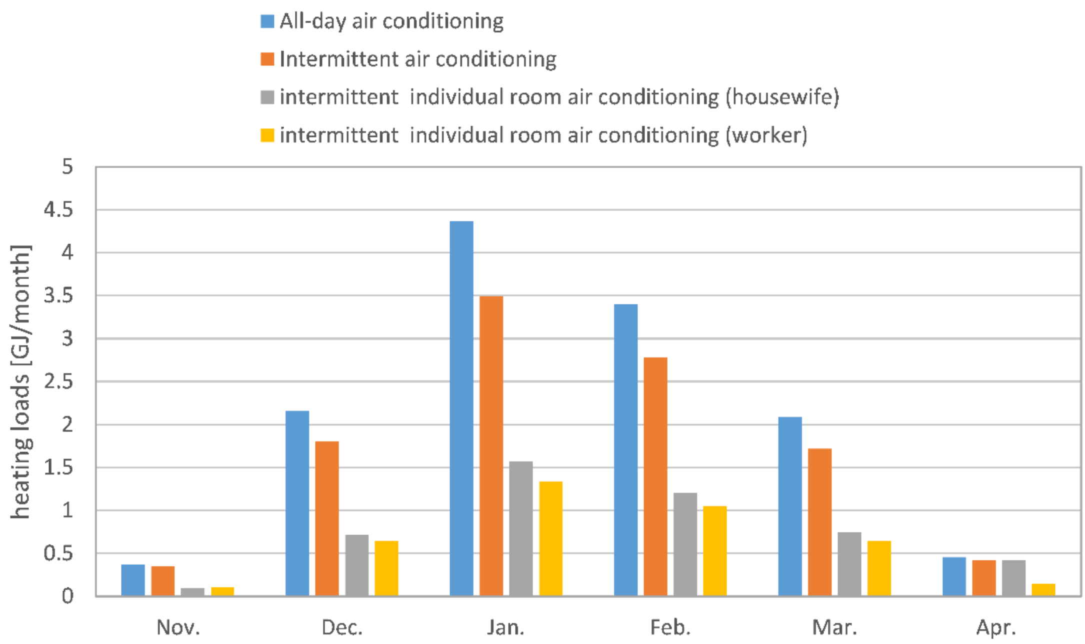

Figure 6.10 Monthly heating load of Model III

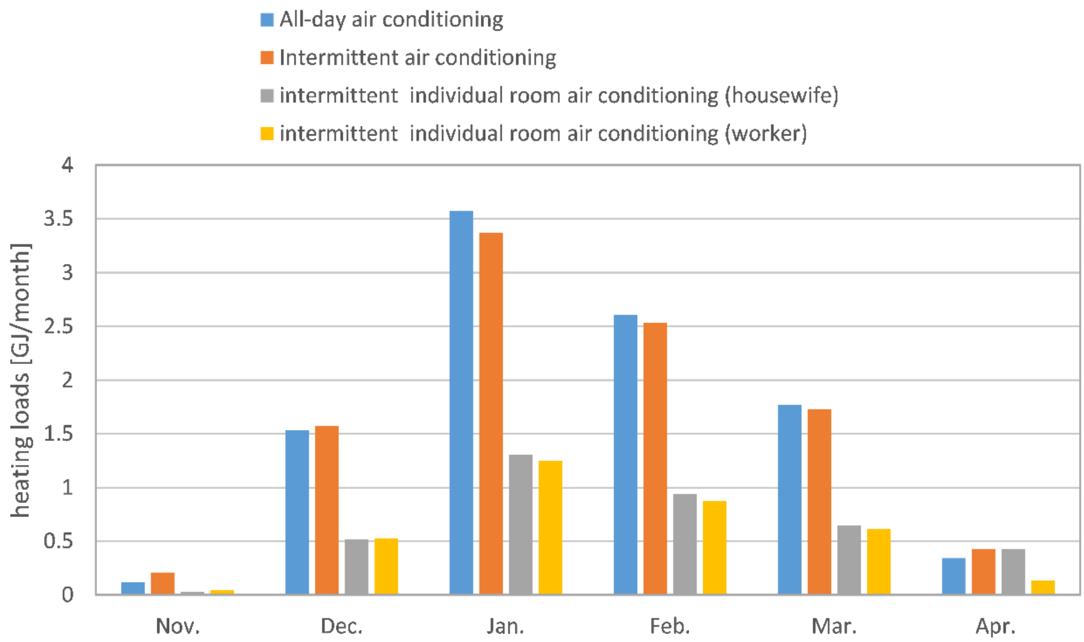

Figure 6.11 Monthly heating load of Model IV

6.4.3. The heating load varies with time (double skin facade)

Figures 6.12 and 6.13 show the heating load of Model III and Model IV over time on two sunny days, respectively. In all Models with intermittent air conditioning or intermittent individual room air conditioning (worker or housewife), the heating load increased when the central air conditioning system is used again after the air conditioning system is stopped. It can be concluded that when the central air conditioning system is turned off, the temperature of the central air conditioning room decreases, and when the central air conditioning system is turned on again, a large amount of energy is required to reach the central air conditioning setting temperature.

In the Models III and IV, the heating load of the intermittent air conditioning is larger than the all-day air conditioning during the period of when the intermittent air conditioning is used. However, the all-day air conditioning uses a large heating load during the period of when the intermittent air conditioning is stopped. Therefore, it can be said that the intermittent air conditioning can reduce the annual heating load compared with the all-day air conditioning (Figure 6.9). In the case of all-day air conditioning, the heating load decreased from 9:00 to 16:00. Model IV has the greatest reduction rate. It can be said that the double skin facade collect heat during the daytime to reduce energy consumption.

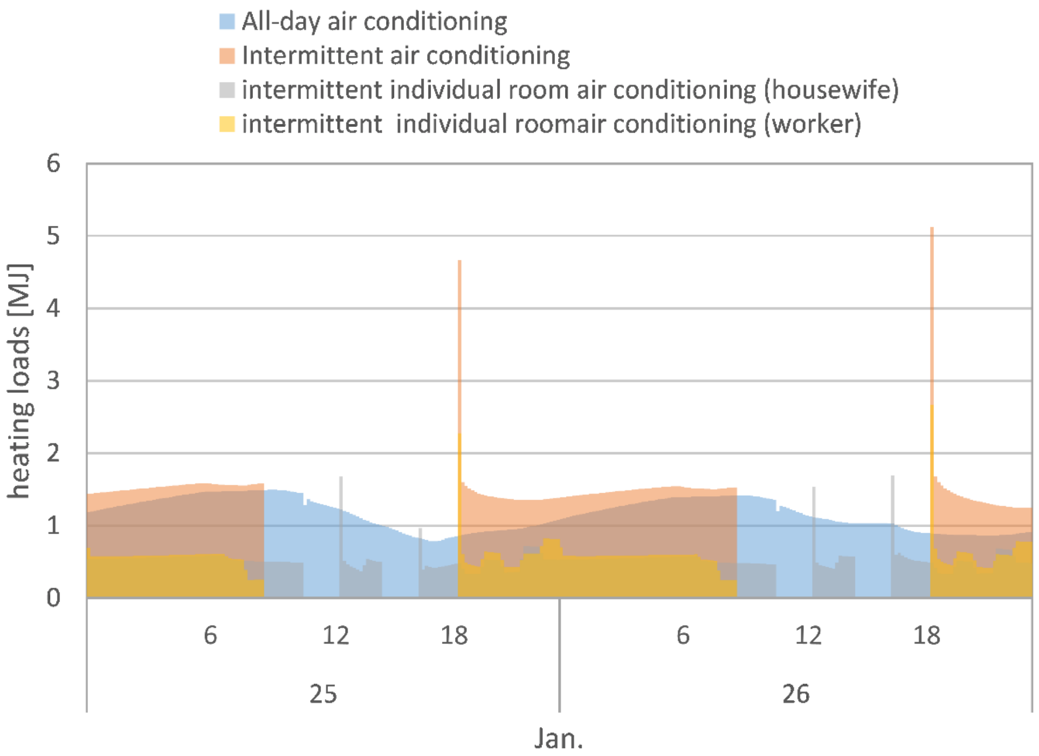

Figure 6.12 The heating load varies with time (Model III)

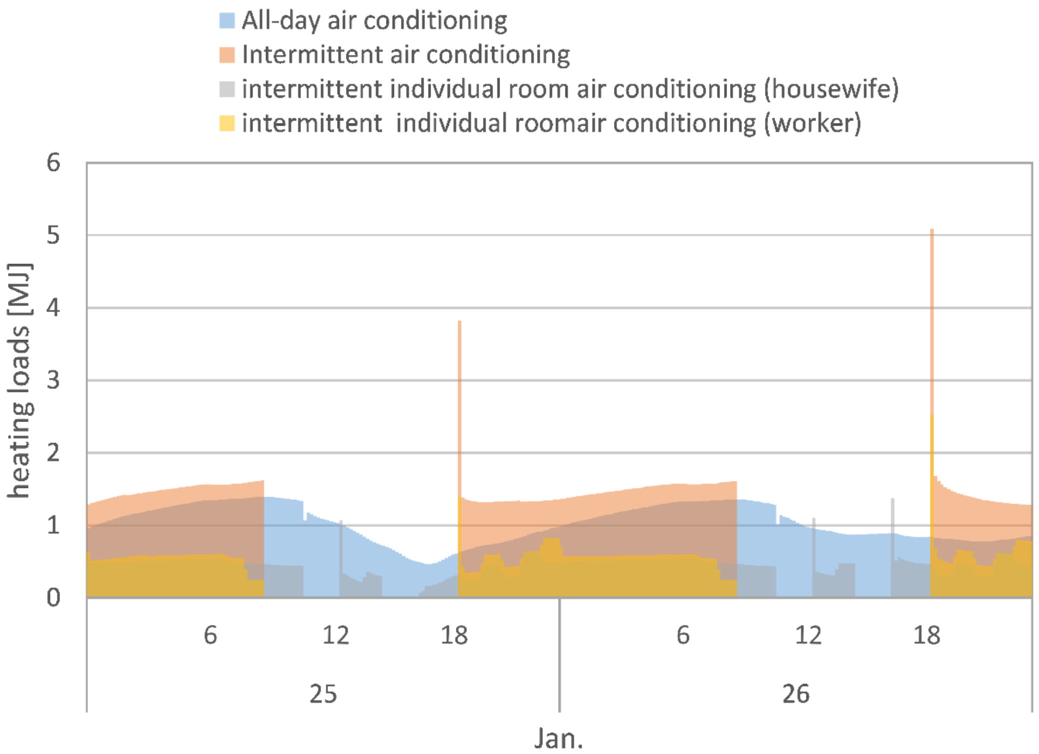

Figure 6.13 The heating load varies with time (Model IV)

6.5. Simulation results (Trombe wall)

6.5.1. Annual heating load (Trombe wall)

Simulation studies were carried out in the case of all-day air conditioning, intermittent air conditioning, intermittent individual room air conditioning (mother is a worker), intermittent individual room air conditioning (mother is a housewife). The air is sent to the central air conditioning room from the Trombe wall only when the temperature inside the Trombe wall is above 24°C. The air circulation between the Trombe wall and central air conditioning room is 500 m^3/h. Figure 6.14 shows the annual heating load of Model Io, Model V, and Model VI. In the case of all-day air conditioning, the annual heating loads of Model Io, Model I and Model II was 14.82 GJ, 12.74 GJ and 8.94 GJ, respectively. In the case of intermittent air conditioning, the annual heating loads of Model Io, Model I and Model II was 11.94 GJ, 10.58 GJ and 9.83 GJ, respectively. In the case of intermittent individual room air conditioning (housewife), the annual heating loads of Model Io, Model I and Model II was 5.60 GJ, 4.58 GJ and 3.86 GJ, respectively. In the case of intermittent individual room air conditioning (worker), the annual heating loads of Model Io, Model I and Model II was 4.58 GJ, 3.81 GJ and 3.26 GJ, respectively. The heating load of Model VI is less than the Model V because Model VI has a large Trombe wall than the Model V. The increase of the space for heat collection prolongs the period of high temperature of the Trombe wall, resulting in an increase in the temperature of the Trombe wall.

In Models V and VI, the case of intermittent individual room air conditioning (worker) used the least energy. In Model V, the case of all-day air conditioning consumed the most energy. In Model VI, the case of intermittent air conditioning consumed the most energy. The case of intermittent individual room air conditioning (housewife) consumed more energy than the case of intermittent individual room air conditioning (worker), but there is not much difference between them. In Model V, the cases of the intermittent air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 2.16 GJ, 8.16 GJ, and 8.92 GJ, respectively, compared to all-day air conditioning. In Model VI, the cases of all-day air conditioning, intermittent individual room air conditioning (housewife), and intermittent individual room air conditioning (worker) save energy by 0.89 GJ, 5.97 GJ, and 6.57 GJ, respectively, compared to intermittent air conditioning.

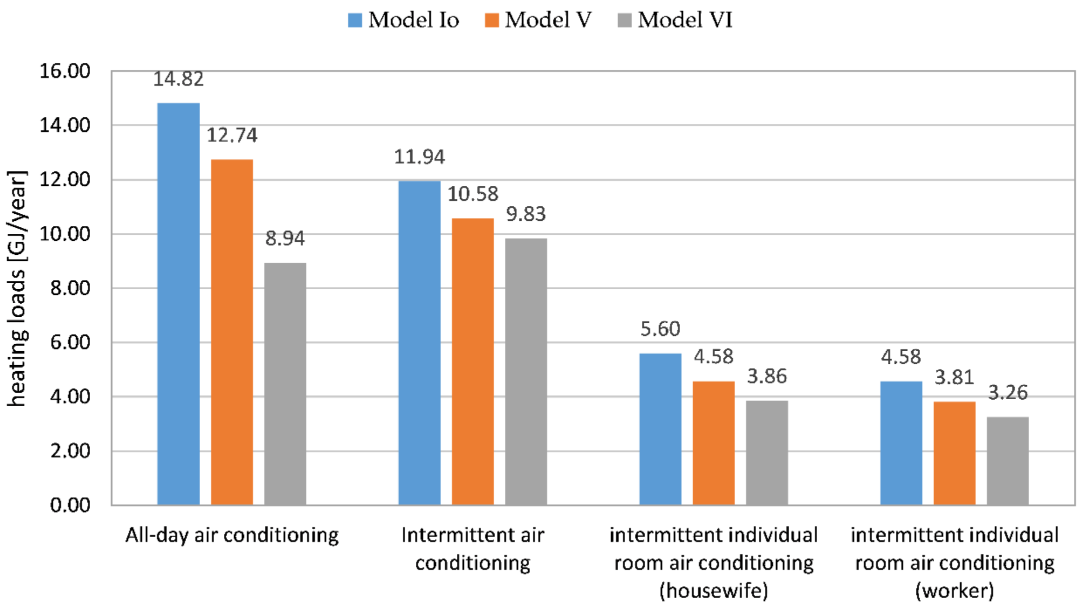

Figure 6.14 Annual heating load of Model Io, Model V, and Model VI

6.5.2. Monthly heating load (Trombe wall)

Figure 6.15 and Figure 6.16 show the monthly heating load of model I and model II, respectively. The heating load in January is the largest in three Models with different air conditioning methods. Since the average temperature in January was the lowest, it was considered that the heating load was affected by the outside air temperature. When the outdoor air temperature is high (April and November), the heating load difference between intermittent individual room air conditioning, all-day air conditioning and intermittent air conditioning is small. When the outdoor air temperature is low (January, February, and March), for Model V, there is a large difference in the heating load between all-day air conditioning and intermittent individual room air conditioning (worker). For Model VI, there is a large difference in the heating load between intermittent air conditioning and intermittent individual room air conditioning (worker).The heating load difference between intermittent individual room air conditioning, all-day air conditioning and intermittent air conditioning were smaller in Model VI. It can be said that the heating load reduction effect by air circulation between the Trombe wall and the central air conditioning room is large in the month of low outside air temperature. It can be said that in the months when the outside air temperature is low, the air circulation between the central air conditioning room and the air cavity of Trombe wall greatly reduced the heating load. In January, the heating load reduction rate of intermittent air conditioning was small, and the reduction rate of all-day air conditioning was large. And the heating load reduction rate of intermittent individual room air conditioning (worker) was small, and the reduction rate of intermittent individual room air conditioning (housewife) was large. If there is a house with a large volume of Trombe wall (Model VI), it is best to use central air conditioning all day.

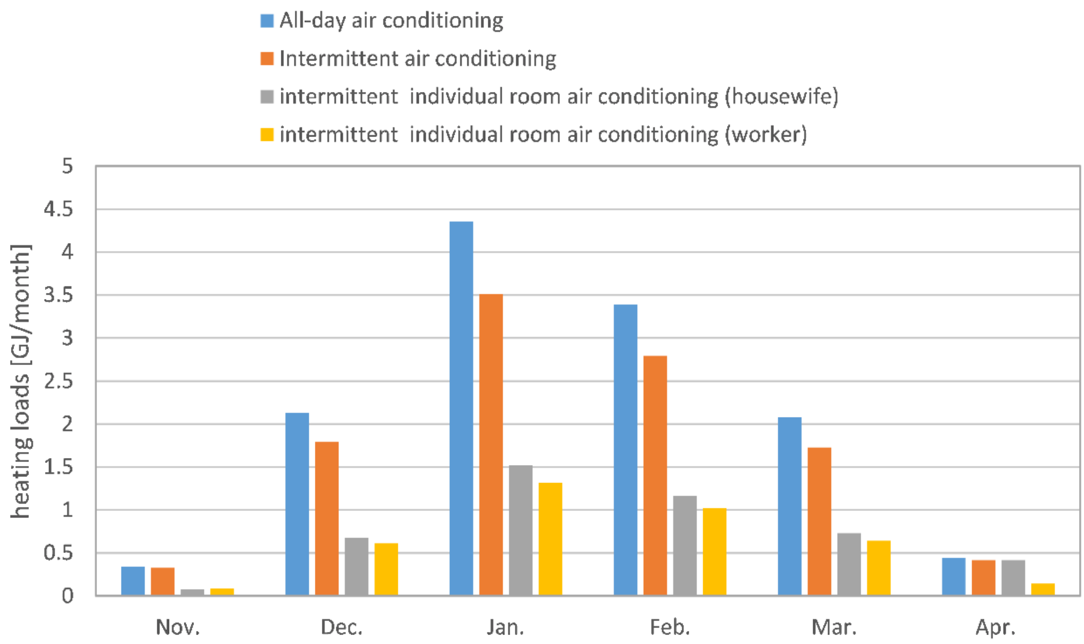

Figure 6.15 Monthly heating load of Model

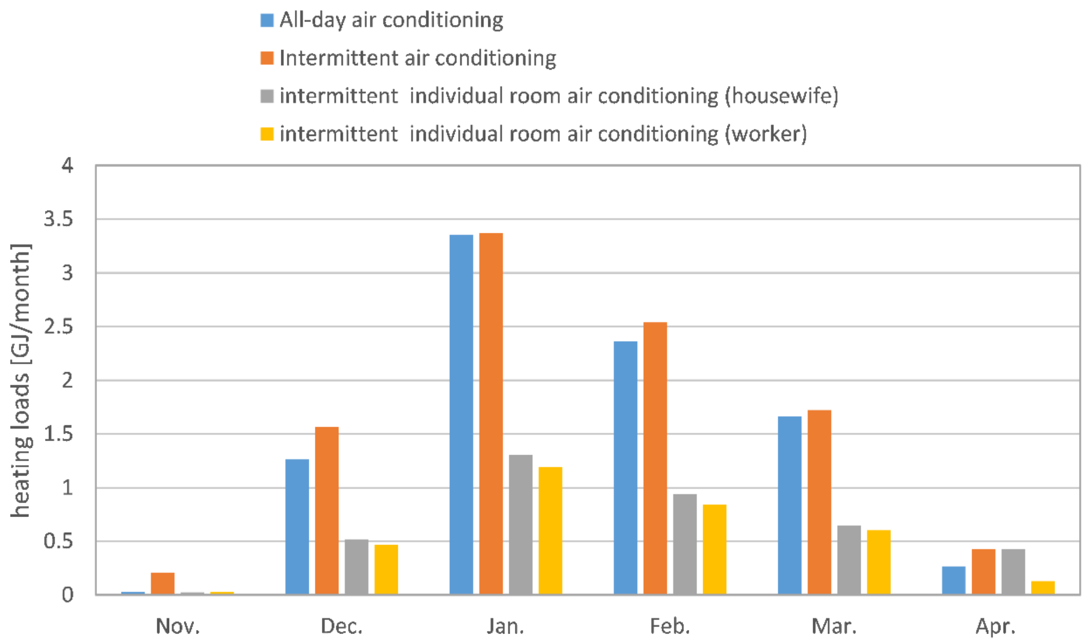

Figure 6.16 Monthly heating load of Model II

6.5.3. The heating load varies with time (Trombe wall)

Figures 6.17 and 6.18 show the heating load of model V and model VI over time on two sunny days, respectively. In all Models with intermittent air conditioning or intermittent individual room air conditioning (worker or housewife), the heating load increased when the central air conditioning system is used again after the air conditioning system is stopped. It can be concluded that when the central air conditioning system is turned off, the temperature of the central air conditioning room decreases, and when the central air conditioning system is turned on again, a large amount of energy is required to reach the central air conditioning setting temperature.

In the Model V, the heating load of the intermittent air conditioning is larger than the all-day air conditioning during the period of when the intermittent air conditioning is used. However, the all-day air conditioning uses a large heating load during the period of when the intermittent air conditioning is stopped. Therefore, it can be said that the intermittent air conditioning can reduce the annual heating load compared with the all-day air conditioning (Figure 6.14). In the case of all-day air conditioning, the heating load decreased from 9:00 to 16:00. Model VI has the greatest reduction rate. It can be said that the Trombe wall collect heat during the daytime to reduce energy consumption.

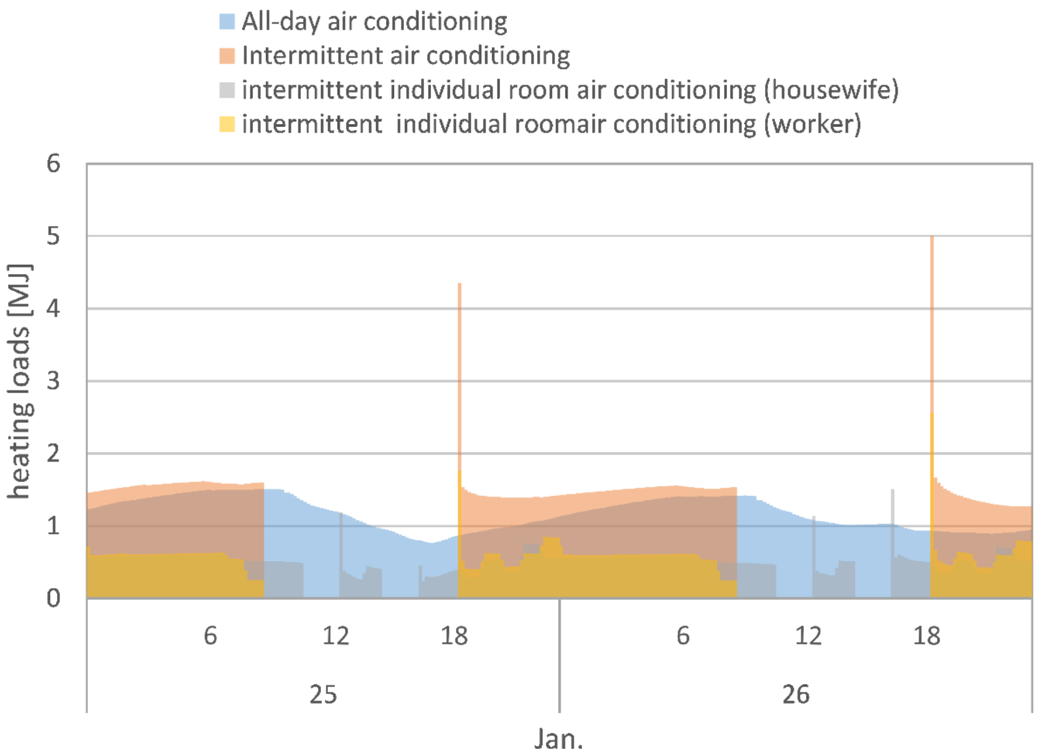

Figure 6.17 The heating load varies with time (Model V)

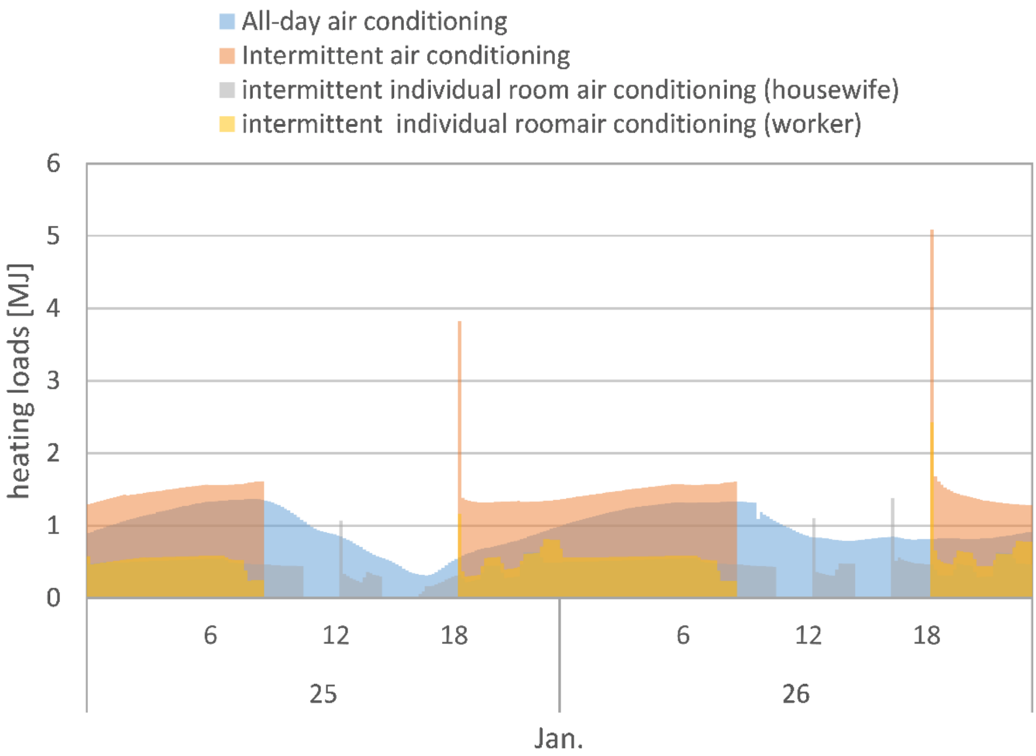

Figure 6.18 The heating load varies with time (Model VI)

6.6. Energy performance

Figures 6.19, 6.20, 6.21 and 6.22 show the annual heating loads of all Models in the case of all-day air conditioning, intermittent air conditioning, intermittent individual room air conditioning (housewife) and intermittent individual room air conditioning (worker), respectively. Compared to the heating load reduction effect of Model Io (a balcony on the second floor), Model II (first- and second-floor sunspace), Model IV (first- and second-floor double skin facade) and Model VI (first- and second-floor Trombe wall) have a larger effect than Model I (first-floor sunspace), Model III (first-floor double skin facade) and Model V (first-floor Trombe wall). These results indicate the larger capacity of the sunspace, double skin facade and Trombe wall structure had a greater heating load reduction effect.

In the case of all-day air conditioning, heating loads of Model VI were smaller than the other Models. Heating loads of Model VI were smaller than Model IV. Heating loads of Model IV were smaller than Model II. Heating loads of Model V were smaller than Model III. Heating loads of Model III were smaller than Model I. These results indicate the Trombe wall has the best energy performance, followed by double skin facade. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 12.18% of energy, about 29.57%, about 13.44%, about 32.88%, about 14.06% and about 39.69%, respectively.

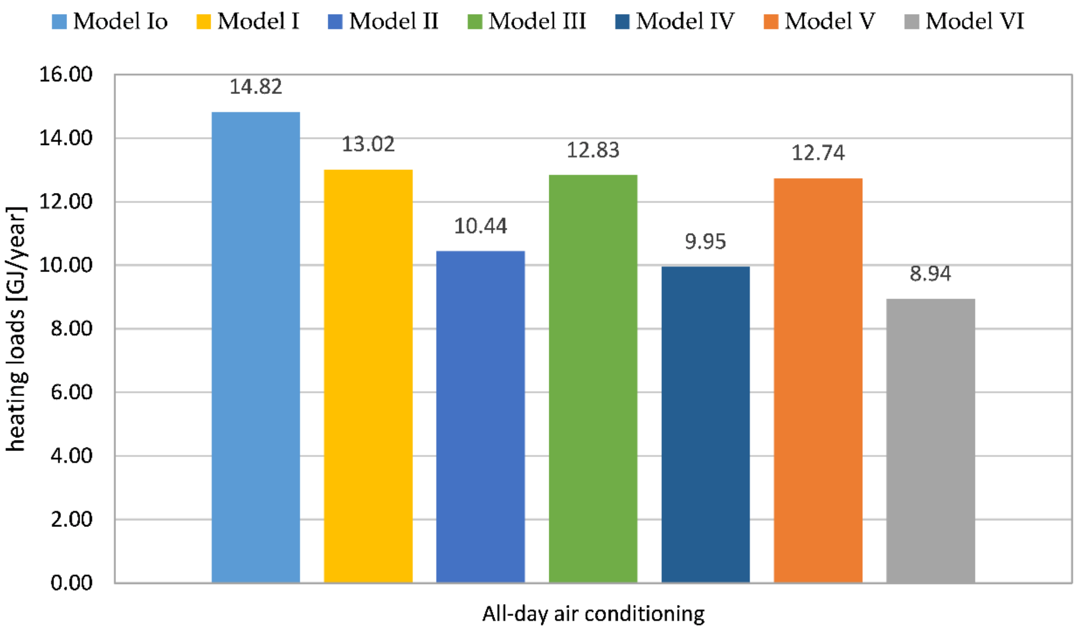

Figure 6.19 Annual heating loads (all-day air conditioning)

In the case of intermittent air conditioning, heating loads of Model VI were smaller than Model II. These results indicate the Trombe wall (first- and second-floor) has the best energy performance, followed by double skin facade (first- and second-floor). Heating loads of Model III were smaller than Model V. Heating loads of Model V were smaller than Model I. These results indicate the double skin facade (first-floor) has the best energy performance, followed by Trombe wall (first-floor). Compared to the Model Io, Models I, II, III, IV, V and VI could save about 10.27% of energy, about 13.03%, about 11.53%, about 17.56%, about 11.43% and about 17.64%, respectively.

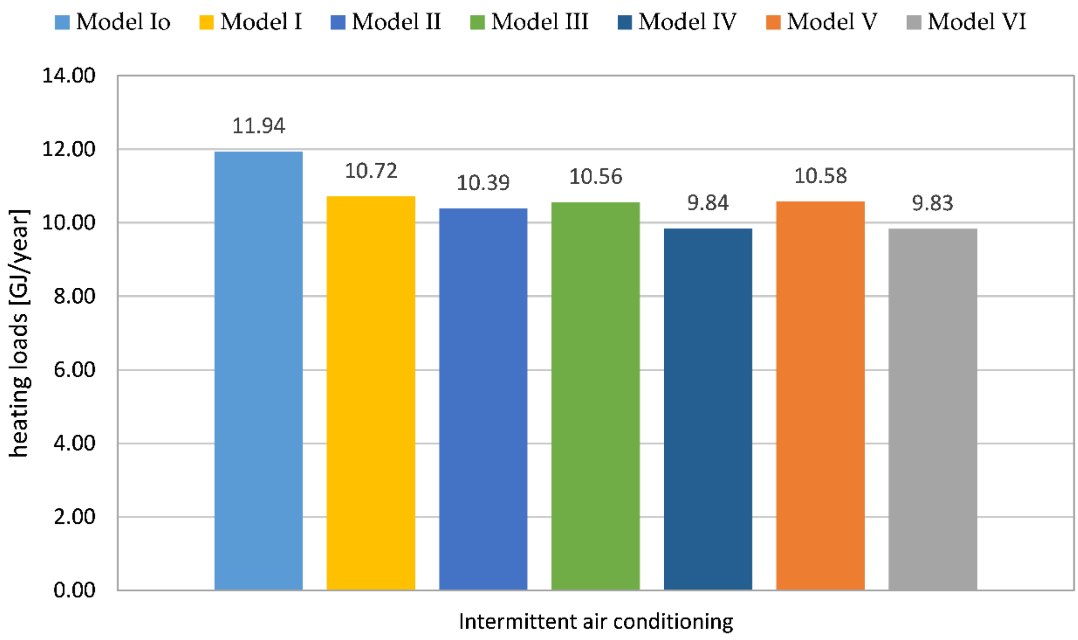

Figure 6.20 Annual heating loads (intermittent air conditioning)

In the case of intermittent individual room air conditioning (housewife), heating loads of Model II were smaller than the other Models. Heating loads of Model II were smaller than Model VI. Heating loads of Model VI were smaller than Model IV. Heating loads of Model I were smaller than Model V. Heating loads of Model V were smaller than Model III. These results indicate the sunspace has the best energy performance, followed by Trombe wall. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 19.40% of energy, about 35.27%, about 15.25%, about 30.95%, about 18.23% and about 31.03%, respectively.

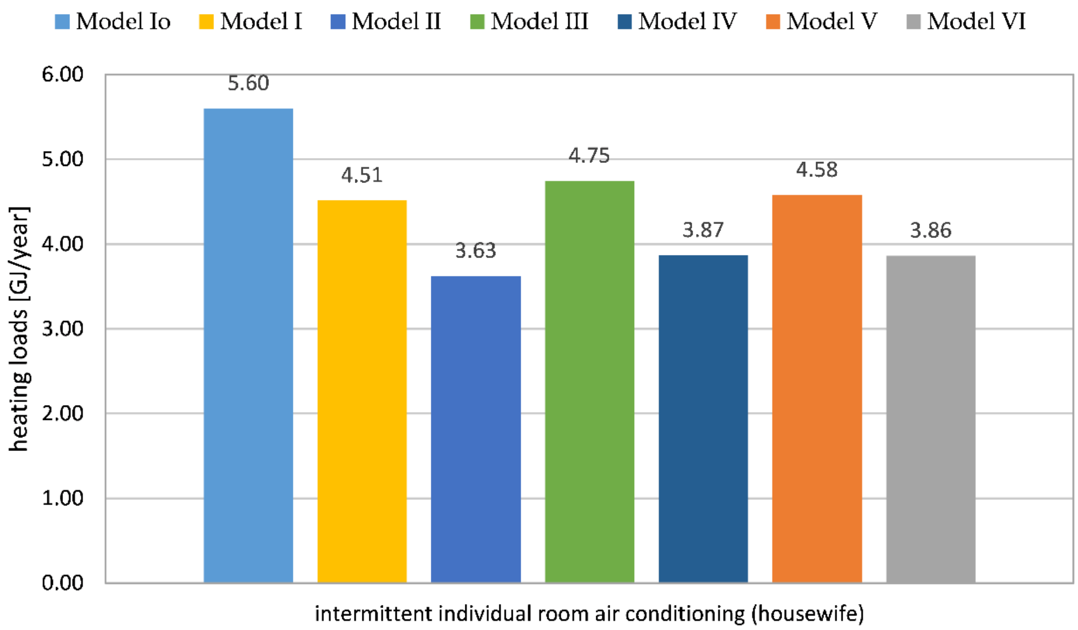

Figure 6.21 Annual heating loads (intermittent individual room air conditioning [housewife])

In the case of intermittent individual room air conditioning (worker), heating loads of Model VI were smaller than the other Models. Heating loads of Model VI were smaller than Model IV. Heating loads of Model IV were smaller than Model II. Heating loads of Model V were smaller than Model III. Heating loads of Model III were smaller than Model I. These results indicate the Trombe wall has the best energy performance, followed by double skin facade. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 13.41% of energy, about 24.38%, about 14.35%, about 24.74%, about 16.67% and about 28.77%, respectively.

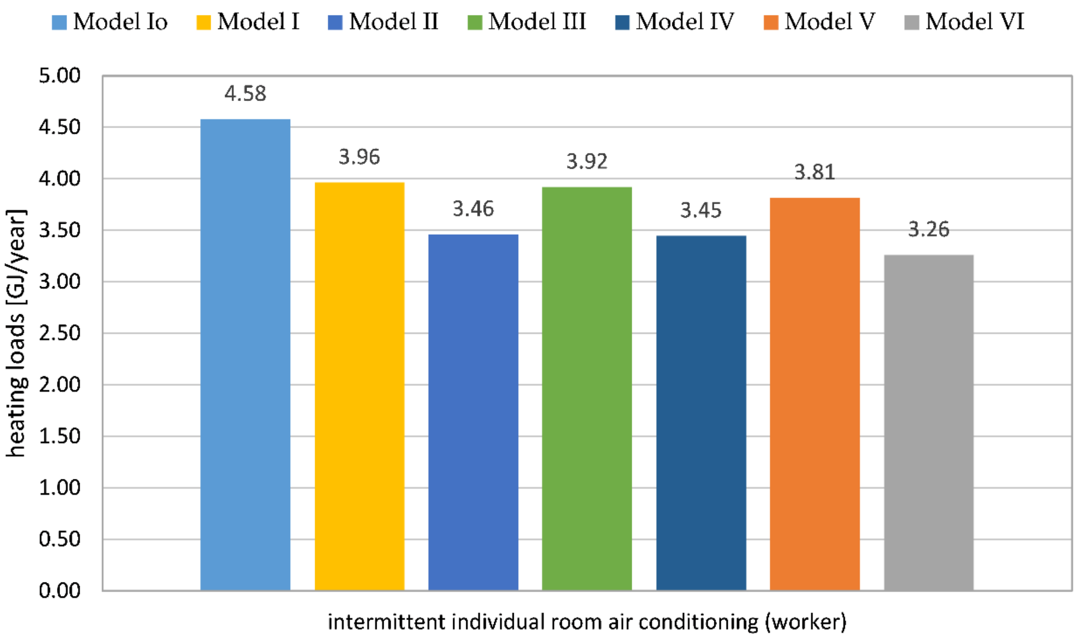

Figure 6.22 Annual heating loads (intermittent individual room air conditioning [worker])

6.7. Summary

In this chapter, numerical studies on the energy performance of the sunspace, DSF (double skin facade) and Trombe wall were carried out. Heating loads were compared betwwen Model Io (a balcony on the second floor), Model I (a sunspace on the second floor [the experimental house]), Model II (the sunspace on the first and second floors), Model III (double skin facade on the second floor), Model IV (double skin facade on the first and second floors), Model V (Trombe wall on the second floor), and Model VI (Trombe wall on the first and second floors).

In all cases, the larger capacity of the sunspace, double skin facade and Trombe wall structure had a greater heating load reduction effect.

In all Models with intermittent air conditioning or intermittent individual room air conditioning, the heating load increased when the air conditioning system is used again after the air conditioning system is stopped. It can be concluded that when the air conditioning system is turned off, the temperature of the air conditioning room decreases, and when the air conditioning system is turned on again, a large amount of energy is required to reach the air conditioning setting temperature.

In the case of all-day air conditioning, the Trombe wall has the best energy performance, followed by double skin facade. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 12.18% of energy, about 29.57%, about 13.44%, about 32.88%, about 14.06% and about 39.69%, respectively.

In the case of intermittent air conditioning, the Trombe wall (first- and second-floor) has the best energy performance, followed by double skin facade (first- and second-floor). The double skin facade (first-floor) has the best energy performance, followed by Trombe wall (first-floor). Compared to the Model Io, Models I, II, III, IV, V and VI could save about 10.27% of energy, about 13.03%, about 11.53%, about 17.56%, about 11.43% and about 17.64%, respectively.

In the case of intermittent individual room air conditioning (housewife), the sunspace has the best energy performance, followed by Trombe wall. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 19.40% of energy, about 35.27%, about 15.25%, about 30.95%, about 18.23% and about 31.03%, respectively.

In the case of intermittent individual room air conditioning (worker), the Trombe wall has the best energy performance, followed by double skin facade. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 13.41% of energy, about 24.38%, about 14.35%, about 24.74%, about 16.67% and about 28.77%, respectively.

Chapter 7.

Numerical analysis of the thermal environment

7. Numerical analysis of the thermal environment

7.1. Introduction

In chapter 6, the effect of reducing heating load by using heat of the sunspace was studied. In this chapter, based on numerical simulation, the thermal environment of each room is studied to check whether it is possible to maintain a comfortable thermal environment. The simulation models and calculation conditions are the same as those in chapter 6.

7.2. Thermal environment of Model Io (a balcony on the second floor)

Figure 7.1 shows the temperature fluctuation of each room in all-day air conditioning. In the case of all-day air conditioning, the model Io which does not have air circulation between the sunspace and the central HVAC room. In the daytime, the each room temperature rises under the influence of the outside air temperature. On the morning of February 22, even though the outdoor temperature was below 0°C, most of the time, the temperature of the LDK, washroom, washroom and hall was kept above 20°C. Therefore, in the case of all-day air conditioning, the central HVAC system can effectively maintain a comfortable temperature for each room. In addition, since the temperature difference in each room is within 5°C, it can be said that the central HVAC system can effectively prevent heat shock.

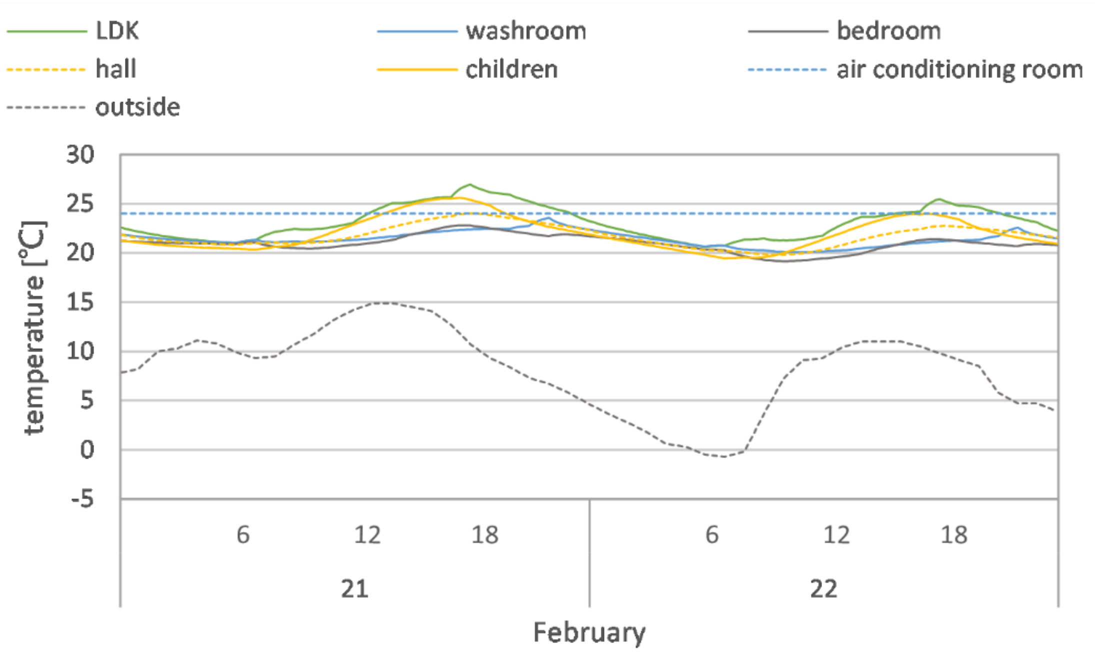

Figure 7.1 The temperature fluctuation of each room in all-day air conditioning

Figure 7.2 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, the central HVAC system is turned off during the daytime (no one is at home). Therefore, the temperature of the washroom, bedroom and central HVAC system room is below 20°C. When the central HVAC system is turned on, the temperature of each room is maintained at 20°C or more for most of the time. Due to solar radiation, the temperature of the children's room and the LDK room in the south is higher than other rooms during the daytime. Although the bedroom faces south, due to the influence of the side walls and roof of the balcony, the temperature of the bedroom is barely affected by solar radiation. In the central HVAC system room, the temperature dropped immediately after the central HVAC was turned off. It can be said that the cold air flows into the central HVAC system room through the total enthalpy heat exchanger.

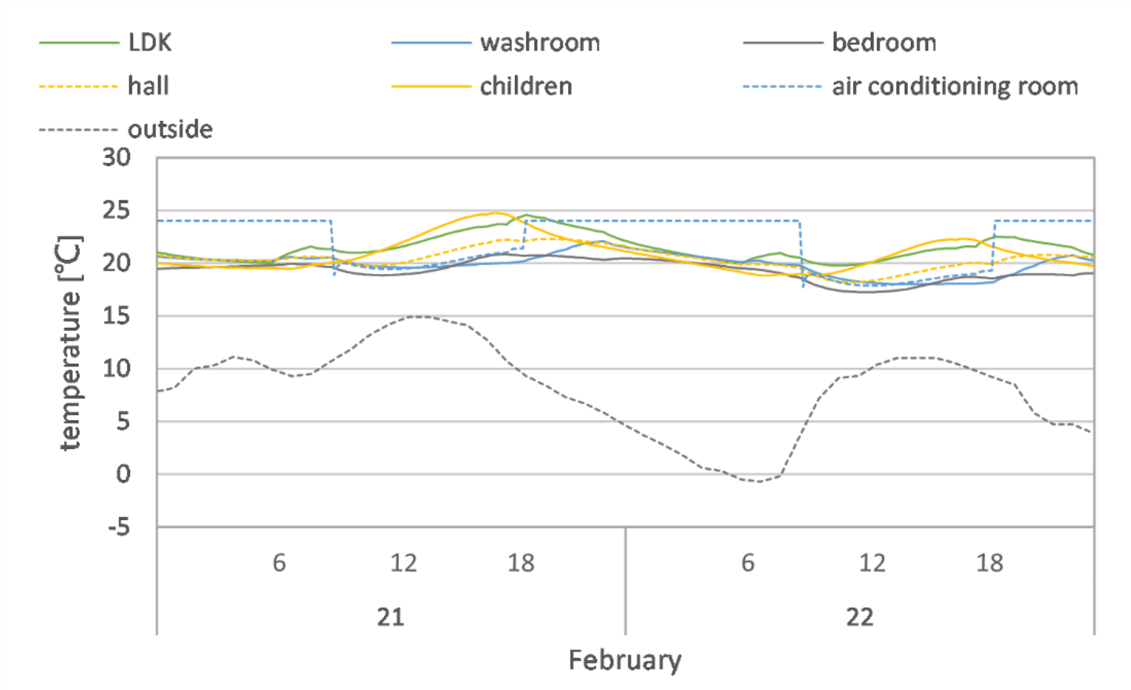

Figure 7.2 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.3 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. However, since the air circulation between the LDK and the central air conditioning system is turned off after 23 o'clock, the temperature of the LDK drops significantly in the morning. In addition, although the air circulation between the LDK and the central air conditioning is turned on in the morning, the LDK temperature can reach 20 °C after twelve o'clock. During the daytime, the LDK reaches a comfortable temperature as the outside air temperature rises and the air circulation between the LDK and the central air conditioner. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for most of the time. The air circulation between the bedroom and the central air conditioning is turned on from 23 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. The temperature in the washroom did not reach 20°C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing.

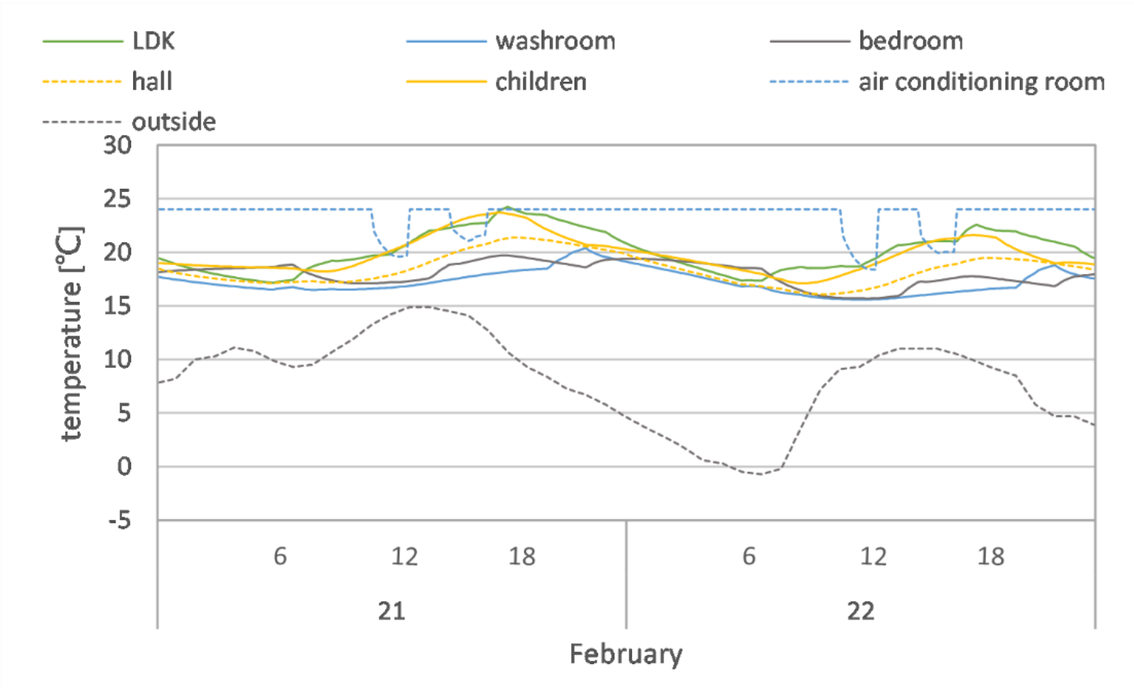

Figure 7.3 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.4 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for most of the time. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. The washroom temperature did not reach 20°C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing. As a result, it is difficult to maintain the comfort temperature of each room in the case of intermittent individual room air conditioning.

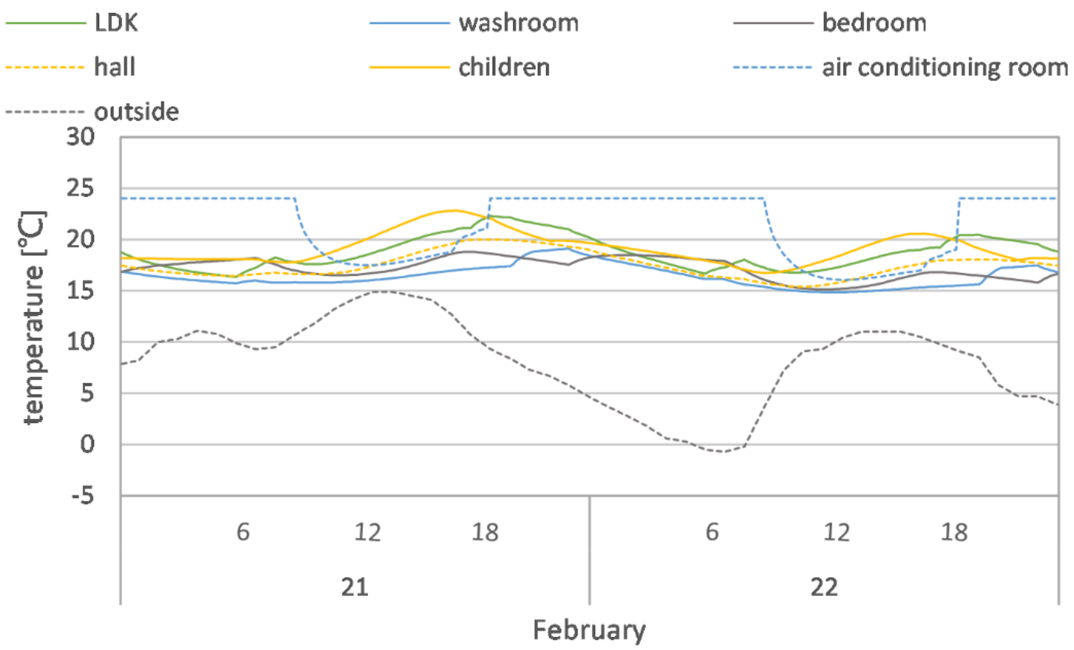

Figure 7.4 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.3. Thermal environment of Model I (a sunspace on the second floor [the experimental house])

Figure 7.5 shows the temperature fluctuation of each room in all-day air conditioning. In the case of all-day air conditioning, even if the heat is sent from the sunspace to the central air conditioning room, the sunspace temperature does not decrease and maintains high temperature. On February 21, after the air circulation between the sunspace and the central air conditioning room began, the temperature of the central air conditioning room rose, but the temperature of the central air conditioning room did not increase on February 22. On February 22, the outdoor temperature was about 5°C lower than on February 21. Therefore, it is not sufficient to use the heat inside the sunspace to heat the cold air that enters through the total enthalpy heat exchanger. On the morning of February

22, the outdoor temperature was lower than 0°C. Except the bedroom and children's room, the temperature of other rooms remained above 20°C for most of the time. Furthermore, compared to Figure 7.1, which shows the temperature fluctuation of each room in all-day air conditioning of model Io (a balcony on the second floor), the decrease in temperature from morning to daytime on the 22nd is small. It is due to the air circulation between the central air conditioning room and the sunspace.

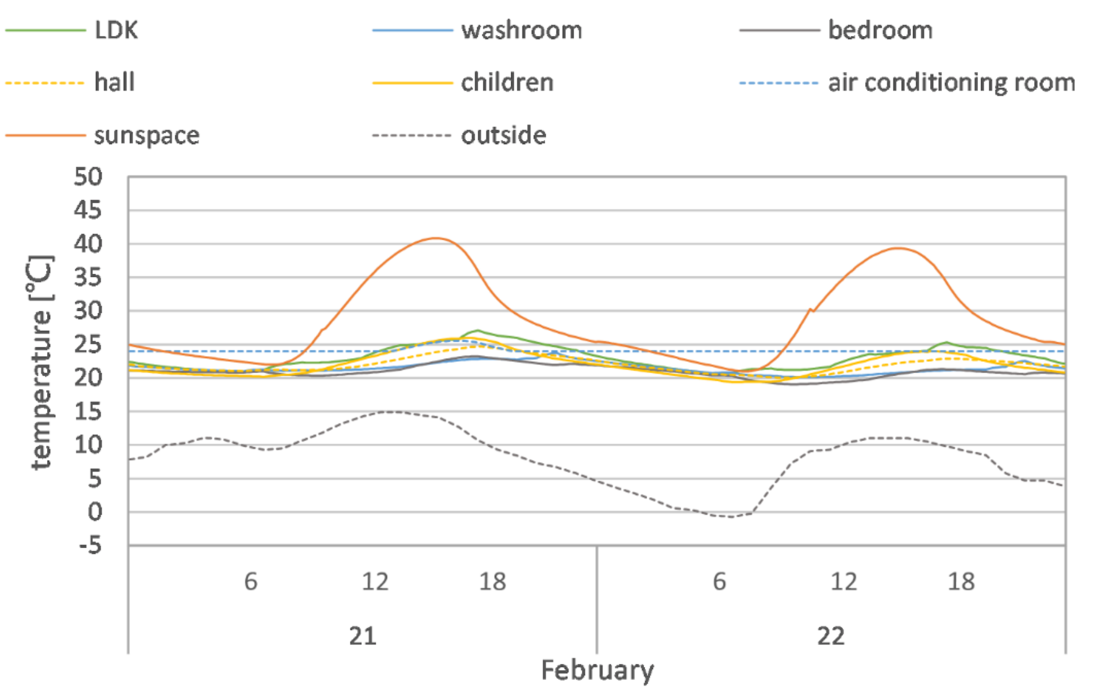

Figure 7.5 The temperature fluctuation of each room in all-day air conditioning

Figure 7.6 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, after the central air conditioning was turned off, it was found that the temperature of the central air conditioning room rose after the sunspace temperature reached 26 °C. At this time, the air flow from the air conditioning room to each room is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. Even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time on February 21, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. At 18 o'clock, the air was sent from the central air conditioning room to the children's room and LDK, and the temperature of the air conditioning room dropped sharply. The amount of air sent to the children's room was 560 m^3/h, and the amount of air sent to LDK was 840 m^3/h. It can be said that the heat in central air conditioning rooms is used excessively.

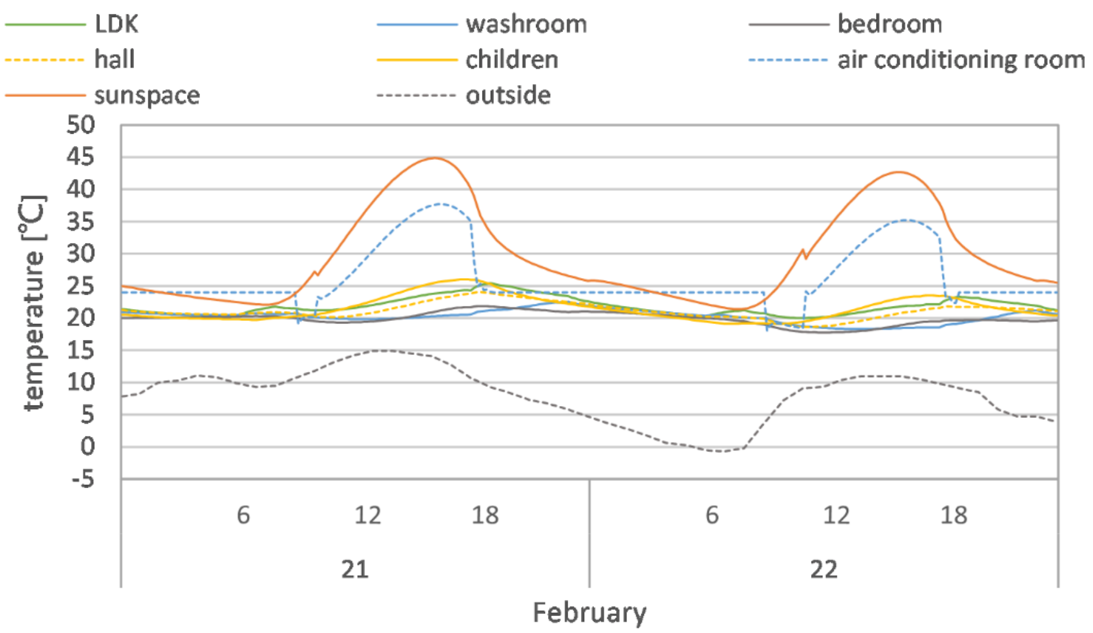

Figure 7.6 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.7 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the central air conditioning room temperature fluctuates due to air circulation between the LDK and the central air conditioning room and intermittent air conditioning. With the exception of the LDK, the air flow from the air conditioning room to each other rooms is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. In addition, due to the increase of the outside air temperature and the air circulation between the central air conditioning room and LDK, the comfort temperature of the LDK during the day has been reached. The LDK temperature dropped in the morning because the central air conditioning system was shut down from 23 o'clock. Furthermore, compared to Figure 7.3, which shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife) of model Io (a balcony on the second floor), the LDK temperature rises earlier. The air was sent to the children's room from 18:00 to 7:00, but the temperature of the children's room decreased as the outside temperature dropped, and was below 20 °C from midnight. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. On the 21st, when the heat in the sunspace was sent to a central air conditioning room, sometimes the bedroom temperature exceeded 20 °C, but most of the time the bedroom temperature was lower than 20°C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. On the 21st, the washroom temperature will exceed 20 °C, but most of the time the washroom temperature is below 20 °C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing.

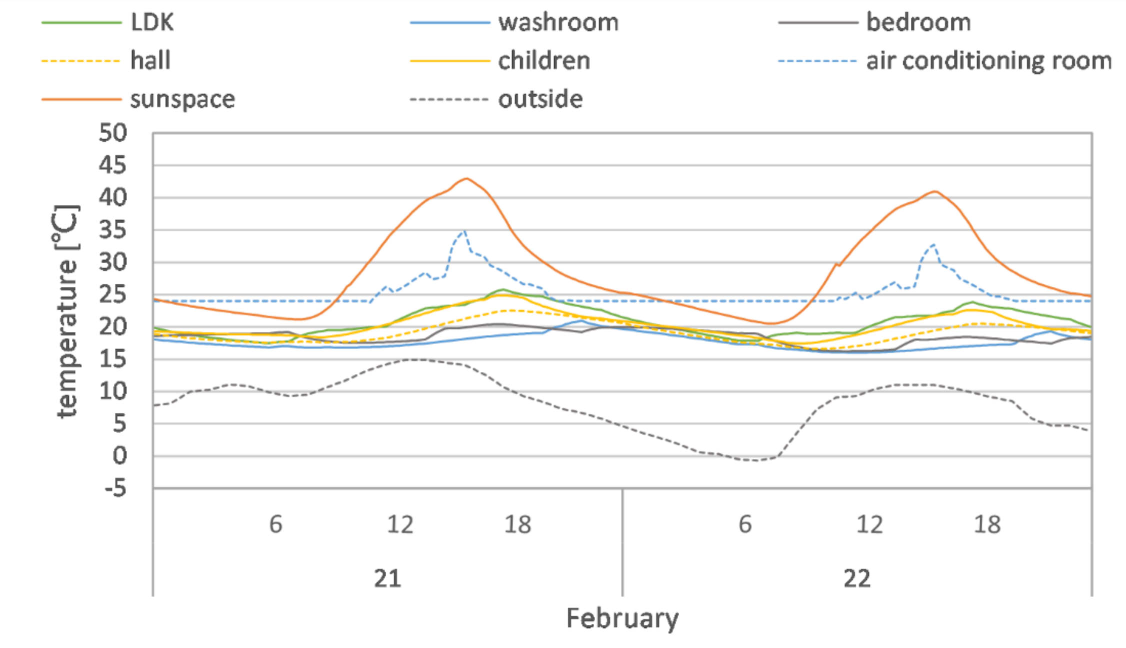

Figure 7.7 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.8 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the sunspace and the central air conditioning room. The temperature of the central air conditioning room rose to about 35°C. Therefore, it is possible to reduce the ratio of the temperature below 20°C during the nighttime by sending the heat from the sunspace to rooms that are not used during the daytime. The air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for most of the time. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. The washroom temperature did not reach 20°C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing. As a result, it is difficult to maintain the comfort temperature of each room in the case of intermittent individual room air conditioning.

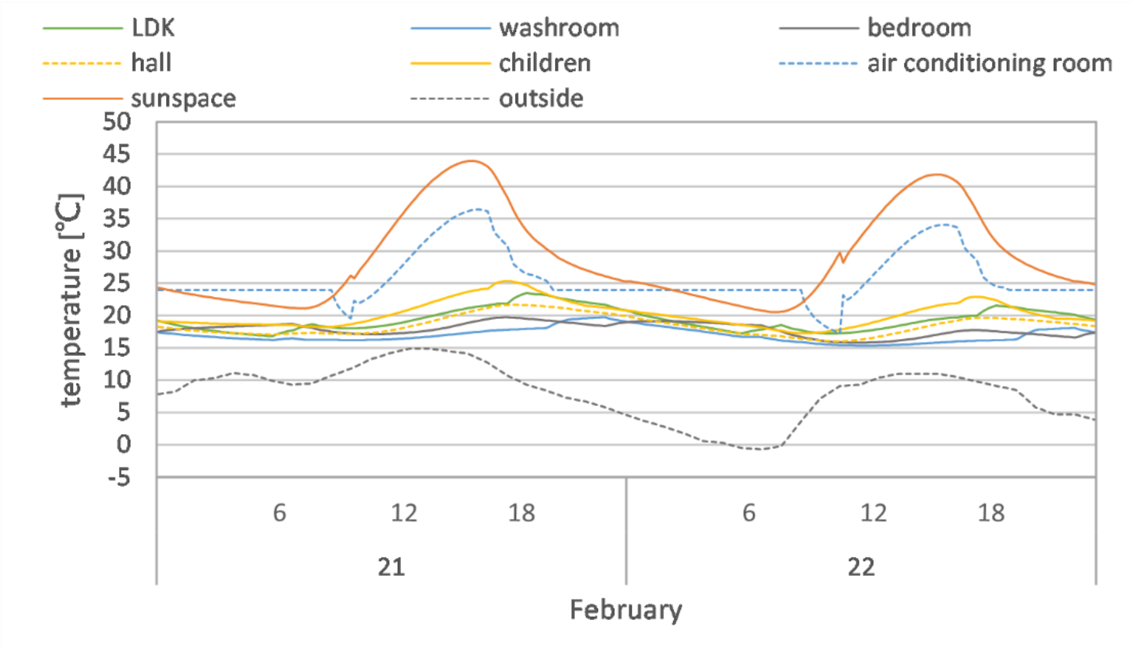

Figure 7.8 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.4. Thermal environment of Model II (the sunspace on the first and second floors)

Figure 7.9 shows the temperature fluctuation of each room in all-day air conditioning. In all air conditioning methods, the temperature of the first floor sunspace is lower than the temperature of the second floor sunspace. The air inside the sunspace on the second floor is sent to the air conditioning room, and the air in the air conditioning room is sent to the sunspace on the first floor. Since there is air movement between the first floor sunspace and second floor sunspace, it can be said that as the warm air moves upwards, the temperature of the second floor sunspace is higher. On the morning of February 22, the outdoor temperature was lower than 0°C. Except the bedroom, the temperature of other rooms remained above 20°C for most of the time.

In the case of all-day air conditioning, the central air conditioning room temperature rose due to the air circulation between in the sunspace and the central air conditioning room. Even if the heat was sent from the sunspace to the central air conditioning room, the sunspace temperature increased. It can be said that the heat inside the sunspace is sufficient. In addition, although the heat is sent from the sunspace to the central air conditioning room, the temperature inside the sunspace is kept high. The maximum temperature of the sunspace is about 10 ° C higher than the sunspace of model I. It can be said that the temperature inside the sunspace increases as the volume of the sunspace increases.

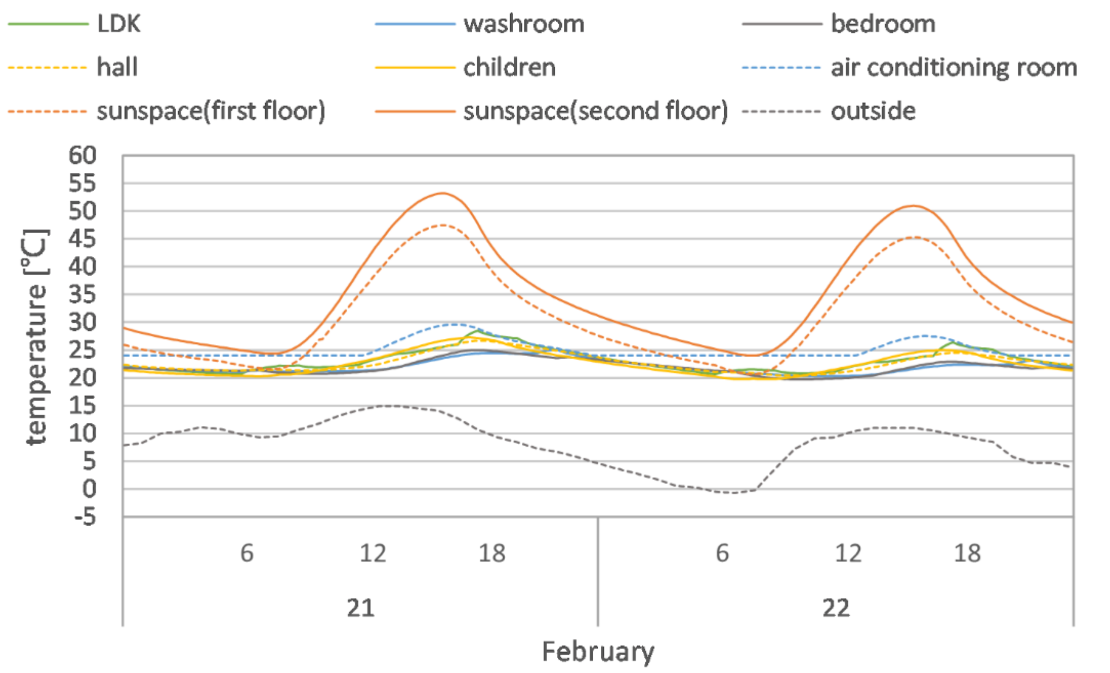

Figure 7.9 The temperature fluctuation of each room in all-day air conditioning

Figure 7.10 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, after the central air conditioning was turned off, it was found that the temperature of the central air conditioning room rose after the sunspace temperature reached 26 °C. At this time, the air flow from the air conditioning room to each room is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. Even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time on February 21, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. At 18 o'clock, the air was sent from the central air conditioning room to the children's room and LDK, and the temperature of the air conditioning room dropped sharply. The amount of air sent to the children's room was 560 m^3/h, and the amount of air sent to LDK was 840 m^3/h. It can be said that the heat in central air conditioning rooms is used excessively.

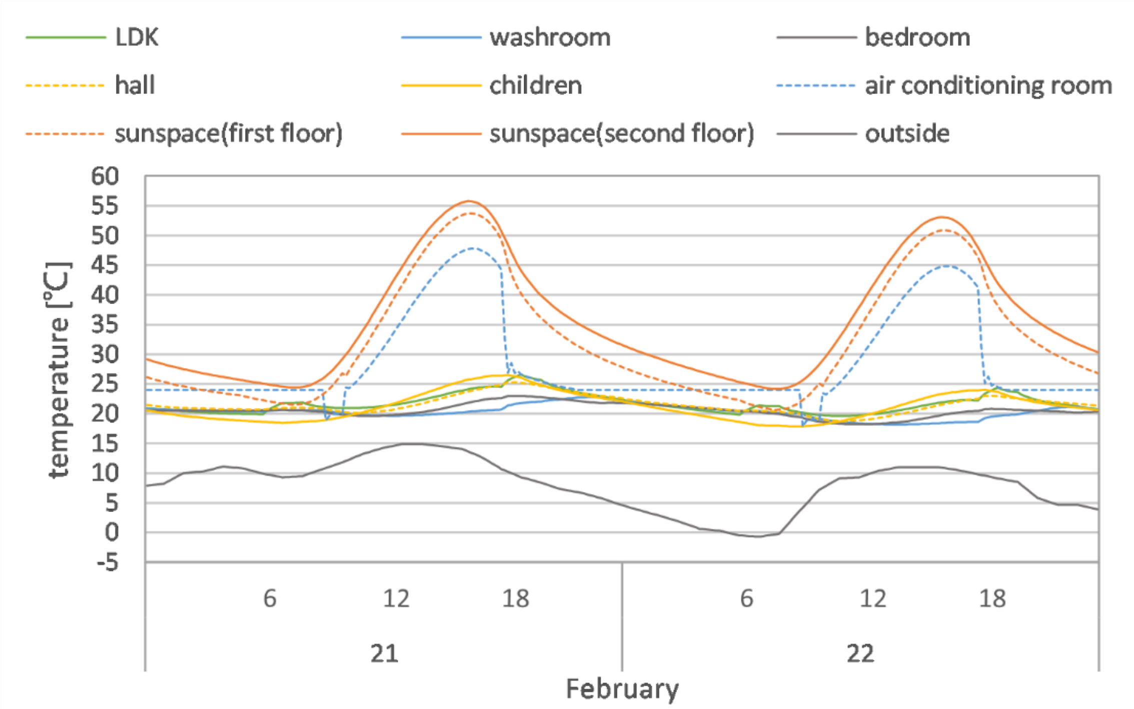

Figure 7.10 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.11 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the central air conditioning room temperature fluctuates due to air circulation between the LDK and the central air conditioning room and intermittent air conditioning. With the exception of the LDK, the air flow from the air conditioning room to each other rooms is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. In addition, due to the increase of the outside air temperature and the air circulation between the central air conditioning room and LDK, the comfort temperature of the LDK during the day has been reached. The LDK temperature dropped in the morning because the central air conditioning system was shut down from 23 o'clock. The air was sent to the children's room from 18:00 to 7:00, but the temperature of the children's room decreased as the outside temperature dropped, and was below 20 °C from 3 o'clock. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is above 20 °C. It is possible to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. Most of the time the washroom temperature was above

20 °C during bathing. The washroom temperature was below 20 °C in other times. The temperature difference between the washroom and the LDK may be close to 8 °C. By opening the door between the LDK and the washroom throughout the day, the LDK can be prevented from overheating and the temperature of the washroom can be raised to create a comfortable thermal environment.

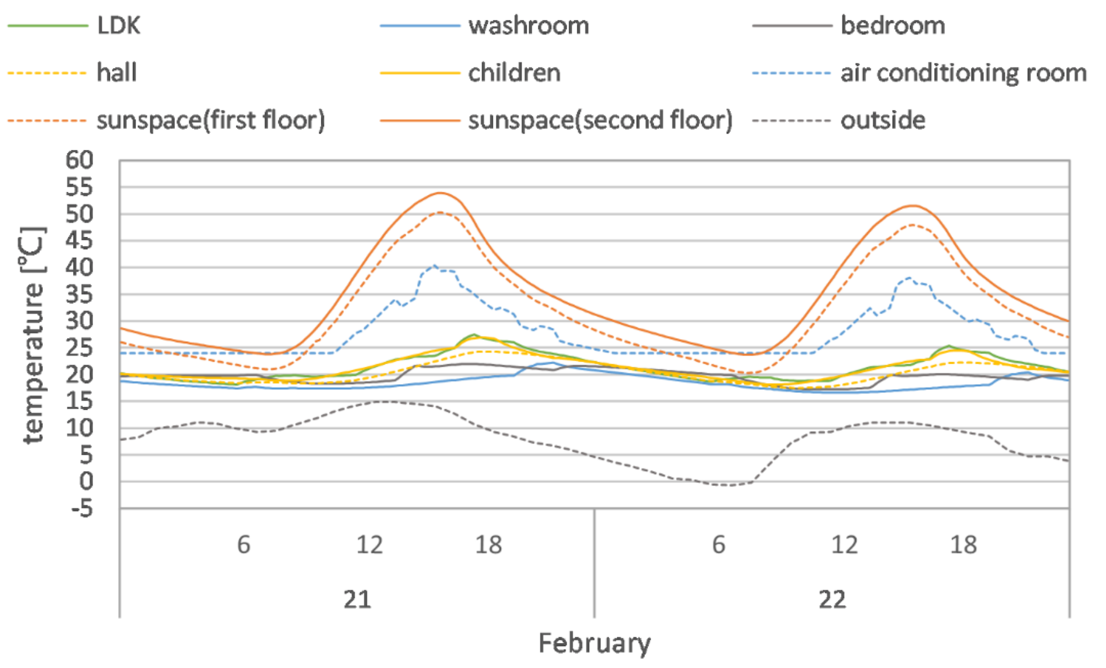

Figure 7.11 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.12 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the sunspace and the central air conditioning room. The temperature of the central air conditioning room rose to about 45°C. Therefore, it is possible to reduce the ratio of the temperature below 20°C during the nighttime by sending the heat from the sunspace to rooms that are not used during the daytime. The air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for 3 o'clock. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. On the 21st, the washroom temperature exceeded 20°C, but it was less than 20°C on the 22nd.

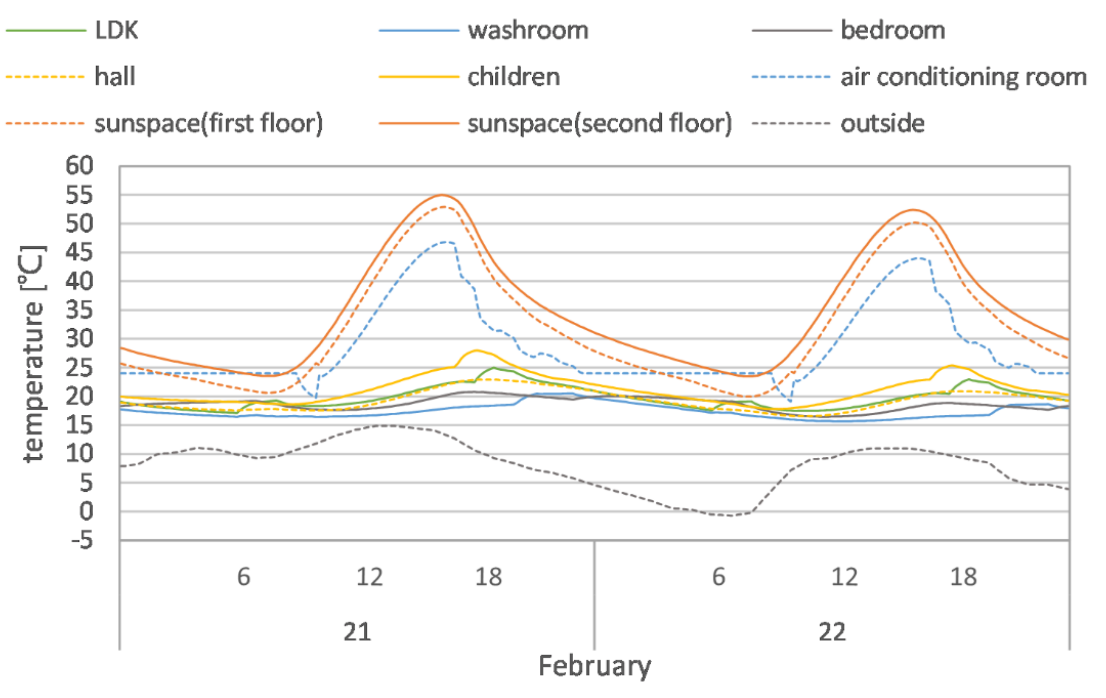

Figure 7.12 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.5. Thermal environment of Model III (the double skin facade on the second floor)

Figure 7.13 shows the temperature fluctuation of each room in all-day air conditioning. In the case of all-day air conditioning, even if the heat is sent from the DSF to the central air conditioning room, the DSF temperature does not decrease and maintains high temperature. On February 21, after the air circulation between the DSF and the central air conditioning room began, the temperature of the central air conditioning room rose, but the temperature of the central air conditioning room did not increase on February 22. On February 22, the outdoor temperature was about 5°C lower than on February 21. Therefore, it is not sufficient to use the heat inside the DSF to heat the cold air that enters through the total enthalpy heat exchanger. On the morning of February 22, the outdoor temperature was lower than 0°C. Except the bedroom and children’s room, the temperature of other rooms remained above 20°C for most of the time. Furthermore, compared to Figure 7.1, which shows the temperature fluctuation of each room in all-day air conditioning of model Io (a balcony on the second floor), the decrease in temperature from morning to daytime on the 22nd is small. It is due to the air circulation between the central air conditioning room and the DSF.

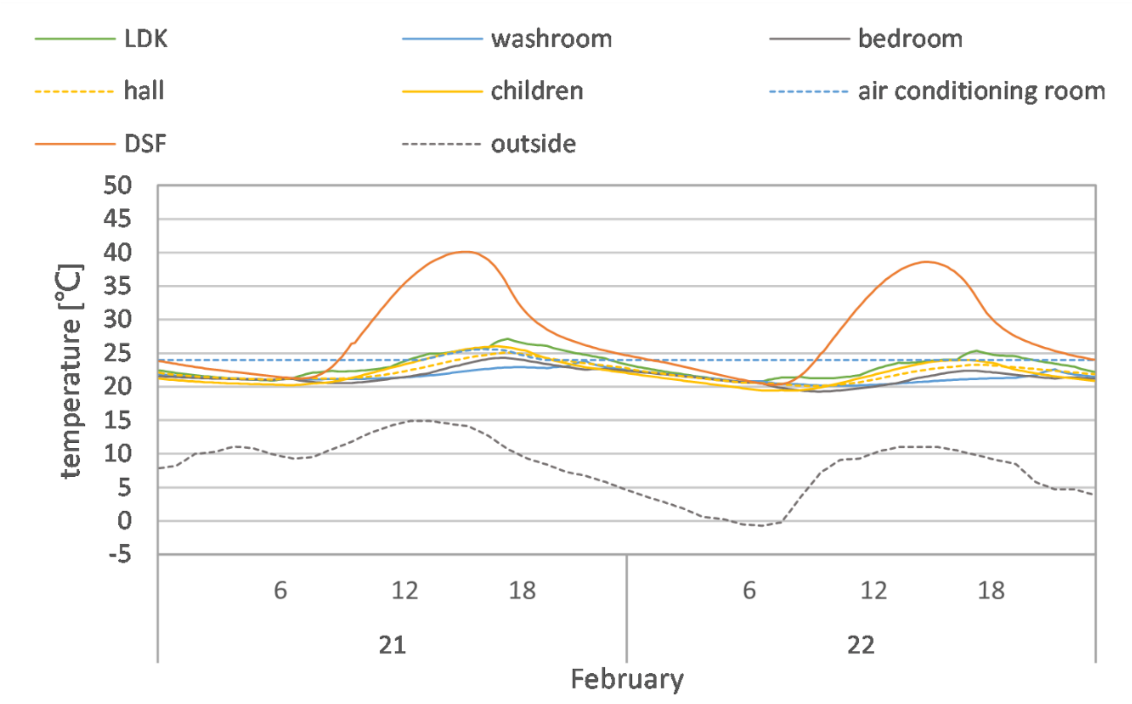

Figure 7.13 The temperature fluctuation of each room in all-day air conditioning

Figure 7.14 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, after the central air conditioning was turned off, it was found that the temperature of the central air conditioning room rose after the DSF temperature reached 26 °C. At this time, the air flow from the air conditioning room to each room is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. Even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time on February 21, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. At 18 o'clock, the air was sent from the central air conditioning room to the children's room and LDK, and the temperature of the air conditioning room dropped sharply. The amount of air sent to the children's room was 560 m^3/h, and the amount of air sent to LDK was 840 m^3/h. It can be said that the heat in central air conditioning rooms is used excessively.

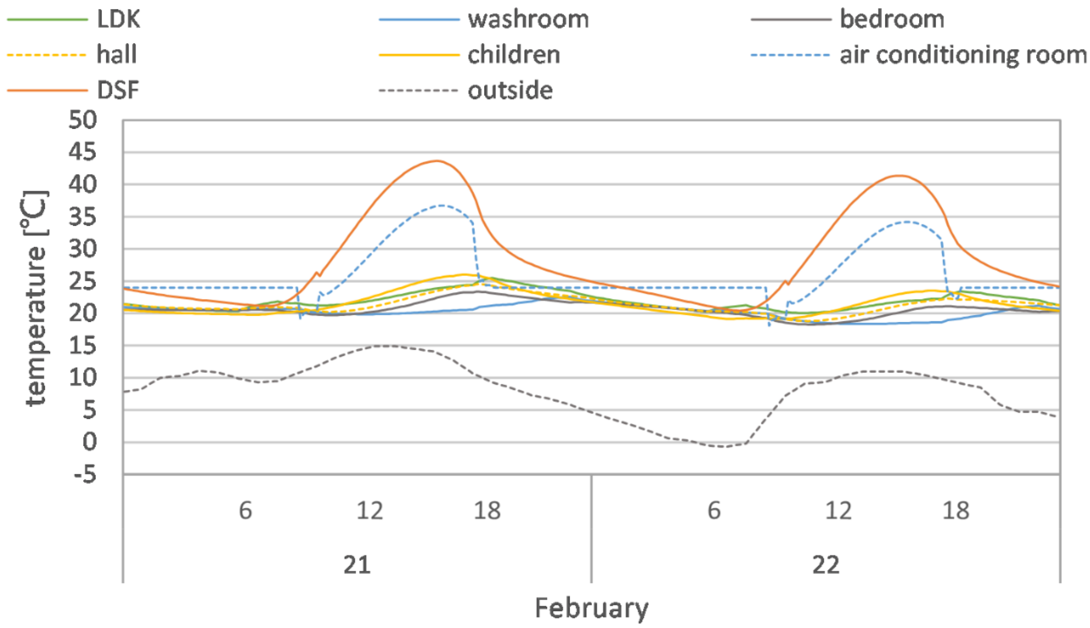

Figure 7.14 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.15 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the central air conditioning room temperature fluctuates due to air circulation between the LDK and the central air conditioning room and intermittent air conditioning. With the exception of the LDK, the air flow from the air conditioning room to each other rooms is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. In addition, due to the increase of the outside air temperature and the air circulation between the central air conditioning room and LDK, the comfort temperature of the LDK during the day has been reached. The LDK temperature dropped in the morning because the central air conditioning system was shut down from 23 o'clock. Furthermore, compared to Figure 7.3, which shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife) of model Io (a balcony on the second floor), the LDK temperature rises earlier. The air was sent to the children's room from 18:00 to 7:00, but the temperature of the children's room decreased as the outside temperature dropped, and was below 20 °C from midnight. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. Half of the time, the bedroom temperature is below 20 °C. The temperature of the bedroom is hard to keep comfortable for half the time. On the 21st, when the heat in the DSF was sent to a central air conditioning room, sometimes the bedroom temperature exceeded 20 °C, but half of the time the bedroom temperature was lower than 20°C. The air circulation between the washroom and the central air conditioning is turned on only during bathing. On the 21st, the washroom temperature will exceed 20 °C, but most of the time the washroom temperature is below 20 °C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing.

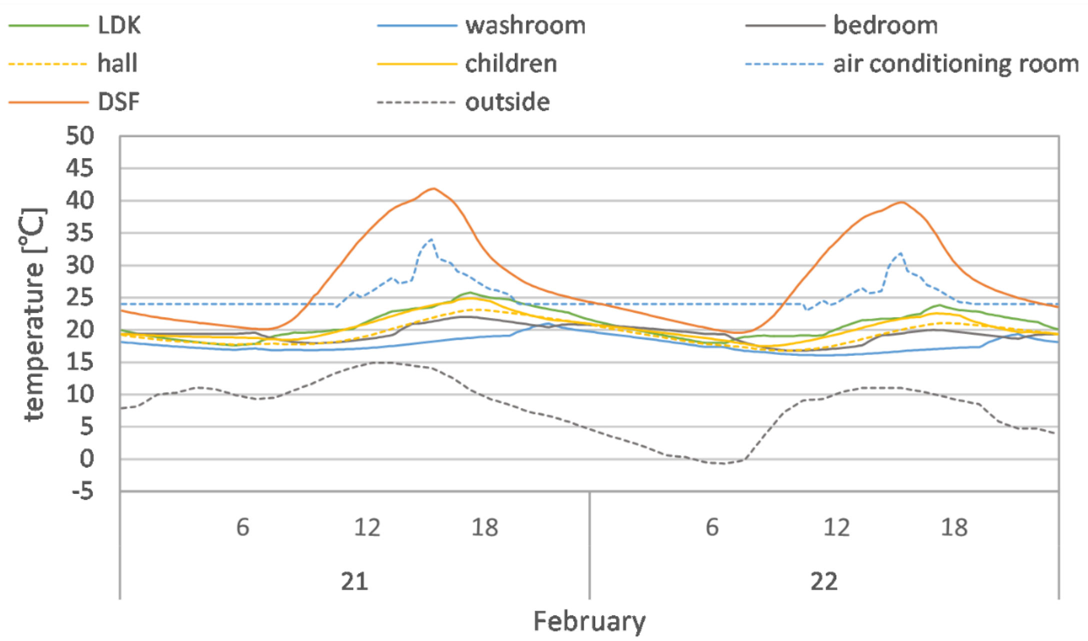

Figure 7.15 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.16 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the DSF and the central air conditioning room. The temperature of the central air conditioning room rose to about 35°C. Therefore, it is possible to reduce the ratio of the temperature below 20°C during the nighttime by sending the heat from the DSF to rooms that are not used during the daytime. The air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for most of the time. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. The washroom temperature did not reach 20°C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing. As a result, it is difficult to maintain the comfort temperature of each room in the case of intermittent individual room air conditioning.

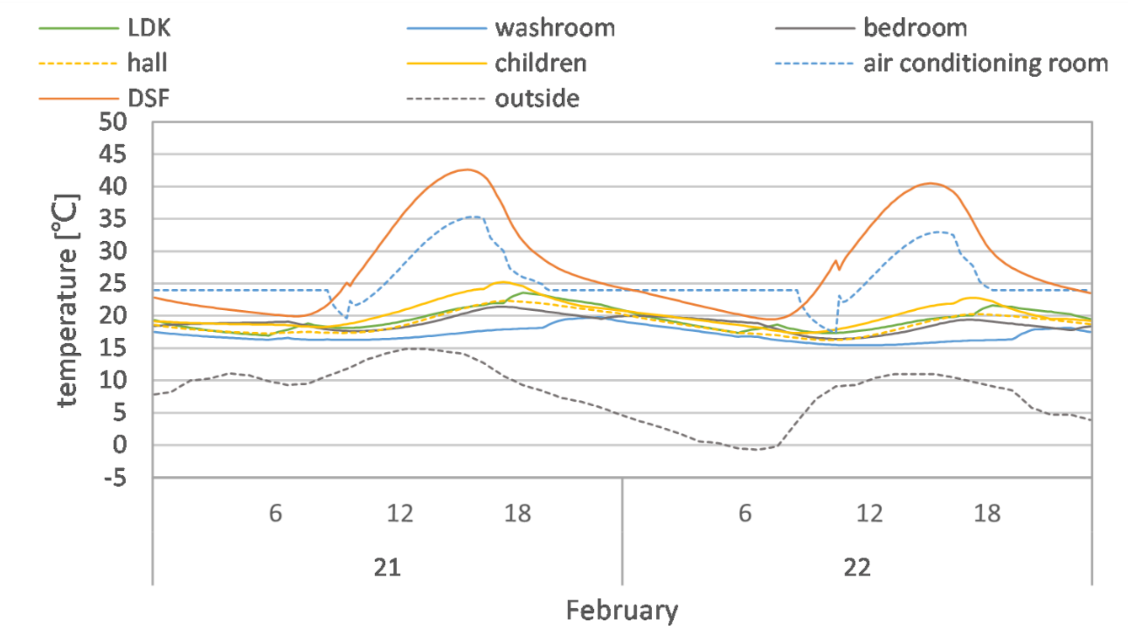

Figure 7.16 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.6. Thermal environment of Model IV (the double skin facade on the first and second floors)

Figure 7.17 shows the temperature fluctuation of each room in all-day air conditioning. In all air conditioning methods, the temperature of the first floor DSF is lower than the temperature of the second floor DSF. The air inside the DSF on the second floor is sent to the air conditioning room, and the air in the air conditioning room is sent to the DSF on the first floor. Since there is air movement between the first floor DSF and second floor DSF, it can be said that as the warm air moves upwards, the temperature of the second floor DSF is higher. On the morning of February 22, the outdoor temperature was lower than 0°C. The temperature in each room is always maintained above 20 °C.

In the case of all-day air conditioning, the central air conditioning room temperature rose due to the air circulation between in the DSF and the central air conditioning room. Even if the heat was sent from the DSF to the central air conditioning room, the DSF temperature increased. It can be said that the heat inside the DSF is sufficient. In addition, although the heat is sent from the DSF to the central air conditioning room, the temperature inside the DSF is kept high. The maximum temperature of the DSF is about 11 °C higher than the DSF of model III. It can be said that the temperature inside the DSF increases as the volume of the DSF increases.

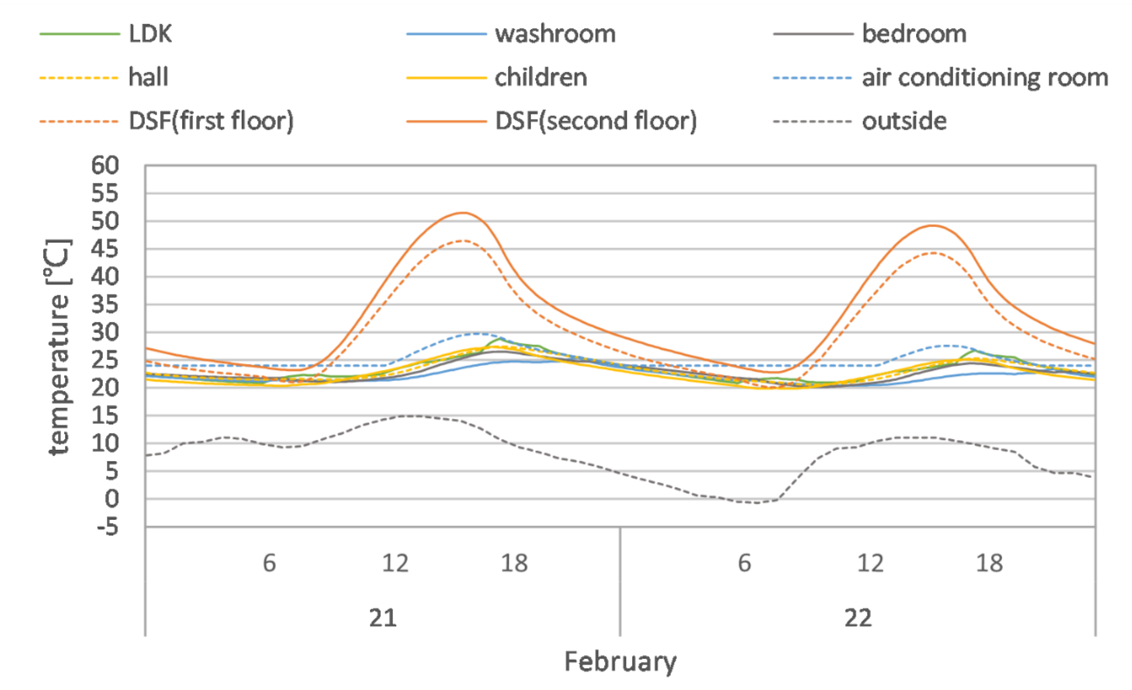

Figure 7.17 The temperature fluctuation of each room in all-day air conditioning

Figure 7.18 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, after the central air conditioning was turned off, it was found that the temperature of the central air conditioning room rose after the DSF temperature reached 26 °C. At this time, the air flow from the air conditioning room to each room is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. Even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time on February 21, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. At 18 o'clock, the air was sent from the central air conditioning room to the children's room and LDK, and the temperature of the air conditioning room dropped sharply.

The amount of air sent to the children's room was 560 m^3/h, and the amount of air sent to LDK was 840 m^3/h. It can be said that the heat in central air conditioning rooms is used excessively.

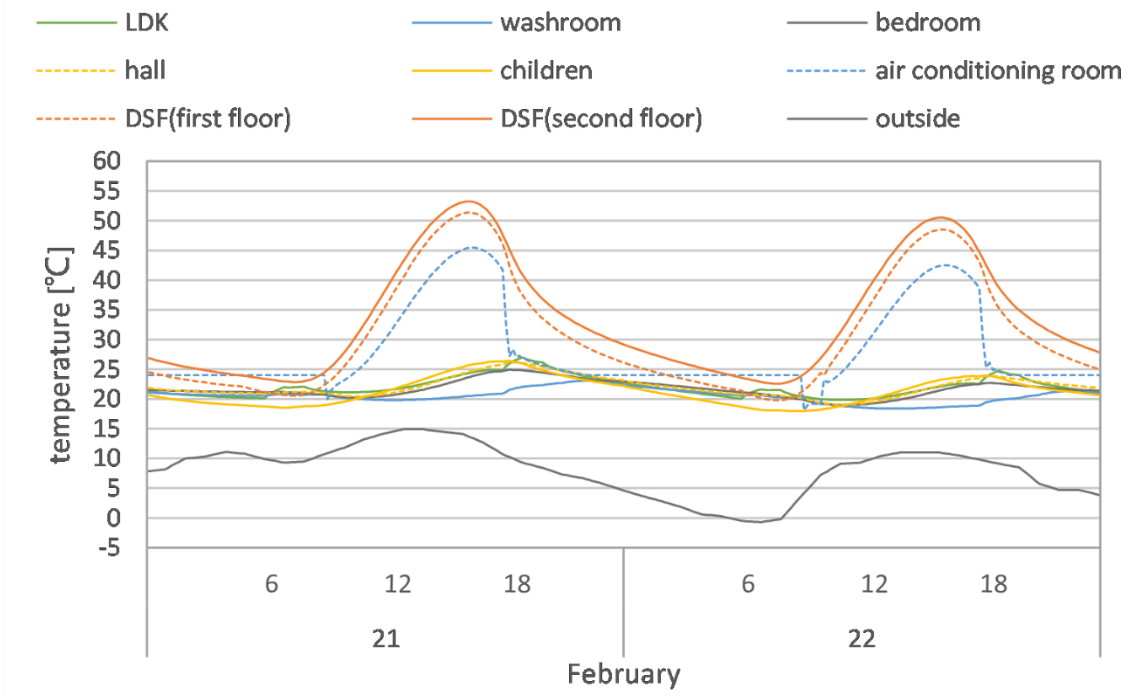

Figure 7.18 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.19 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the central air conditioning room temperature fluctuates due to air circulation between the LDK and the central air conditioning room and intermittent air conditioning. With the exception of the LDK, the air flow from the air conditioning room to each other rooms is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. In addition, due to the increase of the outside air temperature and the air circulation between the central air conditioning room and LDK, the comfort temperature of the LDK during the day has been reached. The LDK temperature dropped in the morning because the central air conditioning system was shut down from 23 o'clock. The air was sent to the children's room from 18:00 to 7:00, but the temperature of the children's room decreased as the outside temperature dropped, and was below 20 °C from 3 o'clock. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is above 20 °C. It is possible to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. Most of the time the washroom temperature was above

20 °C during bathing. The washroom temperature was below 20 °C in other times. The temperature difference between the washroom and the LDK may be close to 8 °C. By opening the door between the LDK and the washroom throughout the day, the LDK can be prevented from overheating and the temperature of the washroom can be raised to create a comfortable thermal environment.

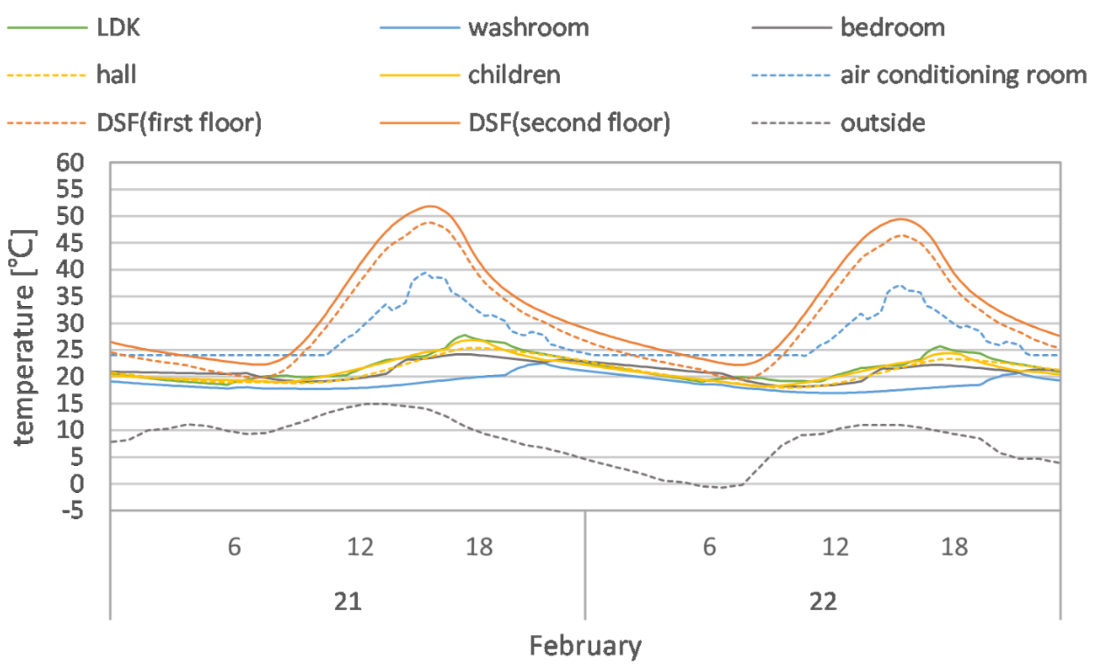

Figure 7.19 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.20 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the DSF and the central air conditioning room. The temperature of the central air conditioning room rose to about 47 °C. Therefore, it is possible to reduce the ratio of the temperature below 20 °C during the nighttime by sending the heat from the DSF to rooms that are not used during the daytime. The air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for 3 o'clock. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. On the 21st, the washroom temperature exceeded 20°C, but it was less than 20°C on the 22nd.

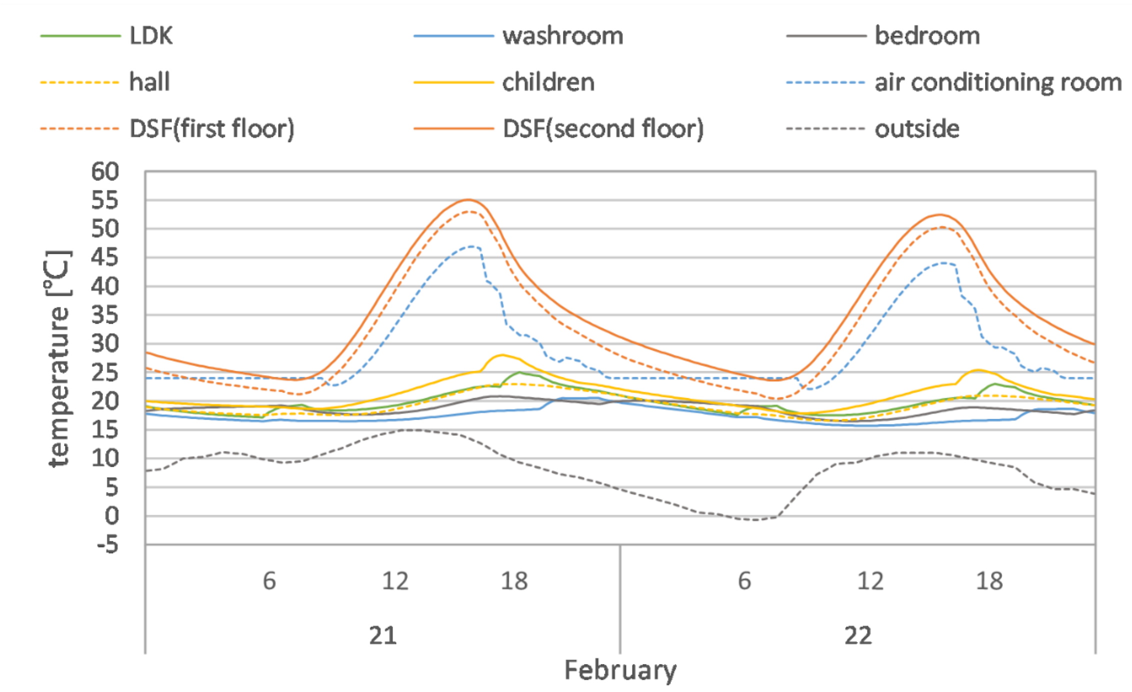

Figure 7.20 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.7. Thermal environment of Model V (the Trombe wall on the second floor)

Figure 7.21 shows the temperature fluctuation of each room in all-day air conditioning. In the case of all-day air conditioning, even if the heat is sent from the Trombe wall to the central air conditioning room, the Trombe wall temperature does not decrease and maintains high temperature. On February 21, after the air circulation between the Trombe wall and the central air conditioning room began, the temperature of the central air conditioning room rose, but the temperature of the central air conditioning room did not increase on February 22. On February 22, the outdoor temperature was about 5 °C lower than on February 21. Therefore, it is not sufficient to use the heat inside the Trombe wall to heat the cold air that enters through the total enthalpy heat exchanger. On the morning of February 22, the outdoor temperature was lower than 0°C. Except the bedroom and children's room, the temperature of other rooms remained above 20°C for most of the time. Furthermore, compared to Figure 7.1, which shows the temperature fluctuation of each room in all-day air conditioning of model Io (a balcony on the second floor), the decrease in temperature from morning to daytime on the 22nd is small. It is due to the air circulation between the central air conditioning room and the Trombe wall.

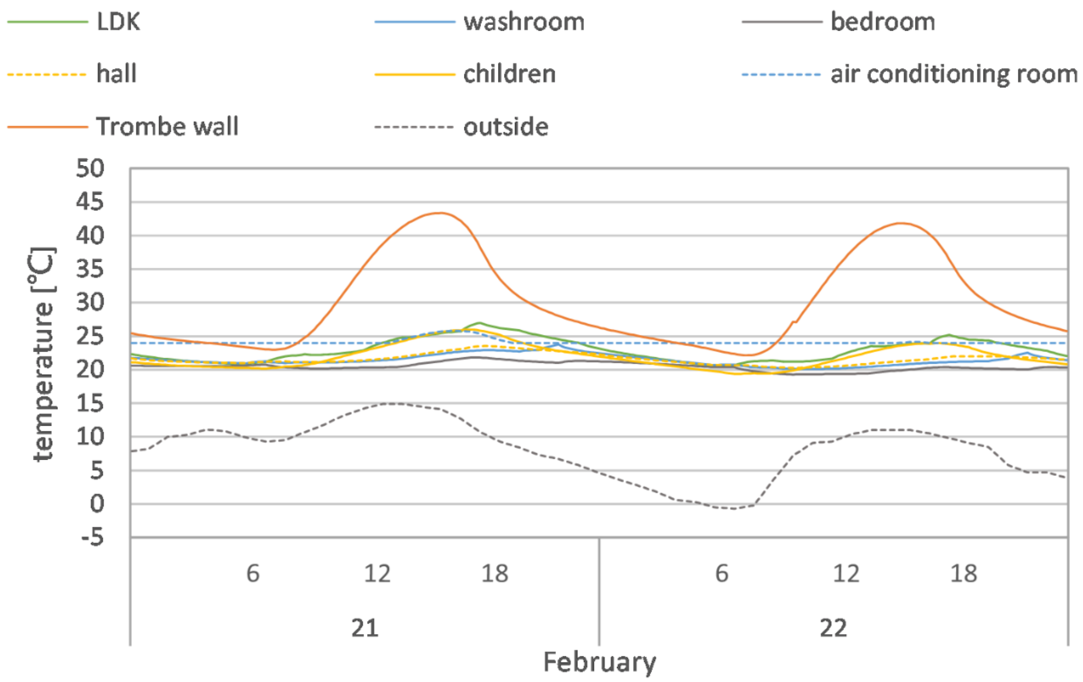

Figure 7.21 The temperature fluctuation of each room in all-day air conditioning

Figure 7.22 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, after the central air conditioning was turned off, it was found that the temperature of the central air conditioning room rose after the Trombe wall temperature reached 26 °C. At this time, the air flow from the air conditioning room to each room is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. Even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time on February 21, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. At 18 o'clock, the air was sent from the central air conditioning room to the children's room and LDK, and the temperature of the air conditioning room dropped sharply. The amount of air sent to the children's room was 560 m^3/h, and the amount of air sent to LDK was 840 m^3/h. It can be said that the heat in central air conditioning rooms is used excessively.

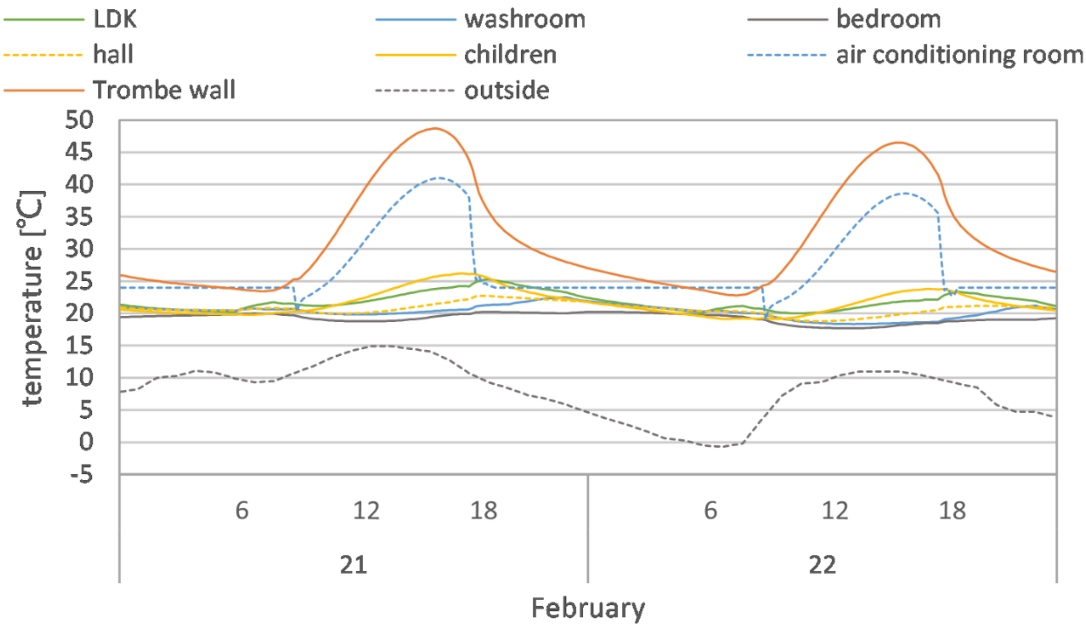

Figure 7.22 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.23 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the central air conditioning room temperature fluctuates due to air circulation between the LDK and the central air conditioning room and intermittent air conditioning. With the exception of the LDK, the air flow from the air conditioning room to each other rooms is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. In addition, due to the increase of the outside air temperature and the air circulation between the central air conditioning room and LDK, the comfort temperature of the LDK during the day has been reached. The LDK temperature dropped in the morning because the central air conditioning system was shut down from 23 o'clock. Furthermore, compared to Figure 7.3, which shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife) of model Io (a balcony on the second floor), the LDK temperature rises earlier. The air was sent to the children's room from 18:00 to 7:00, but the temperature of the children's room decreased as the outside temperature dropped, and was below 20 °C from midnight. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. All the time, the bedroom temperature is below 20 °C. The temperature of the bedroom is hard to keep comfortable. The air circulation between the washroom and the central air conditioning is turned on only during bathing. On the 21st, the washroom temperature will exceed 20 °C, but most of the time the washroom temperature is below 20 °C. The temperature difference between the washroom and other rooms is within 5 °C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing.

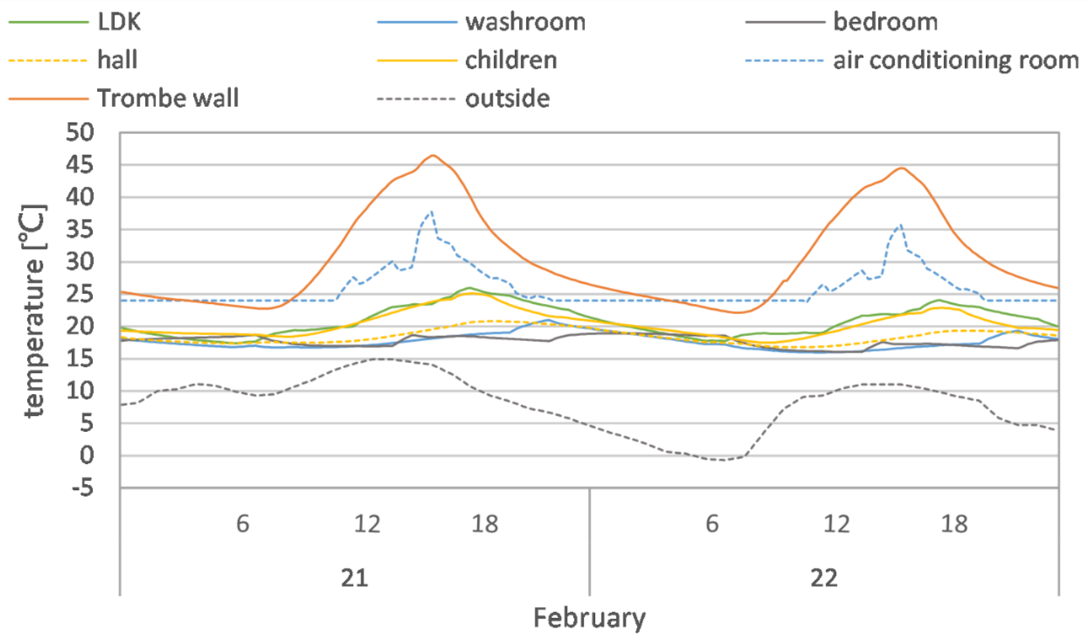

Figure 7.23 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.23 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the Trombe wall and the central air conditioning room. The temperature of the central air conditioning room rose to about 40 °C. Therefore, it is possible to reduce the ratio of the temperature below 20°C during the nighttime by sending the heat from the Trombe wall to rooms that are not used during the daytime. The air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for most of the time. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. The washroom temperature did not reach 20°C. The temperature difference between the washroom and other rooms is within 5°C, which is unlikely to cause heat shock. However, due to uncomfortable temperatures, it is not advisable to open the air circulation between the washroom and the central air conditioning only when bathing. As a result, it is difficult to maintain the comfort temperature of each room in the case of intermittent individual room air conditioning.

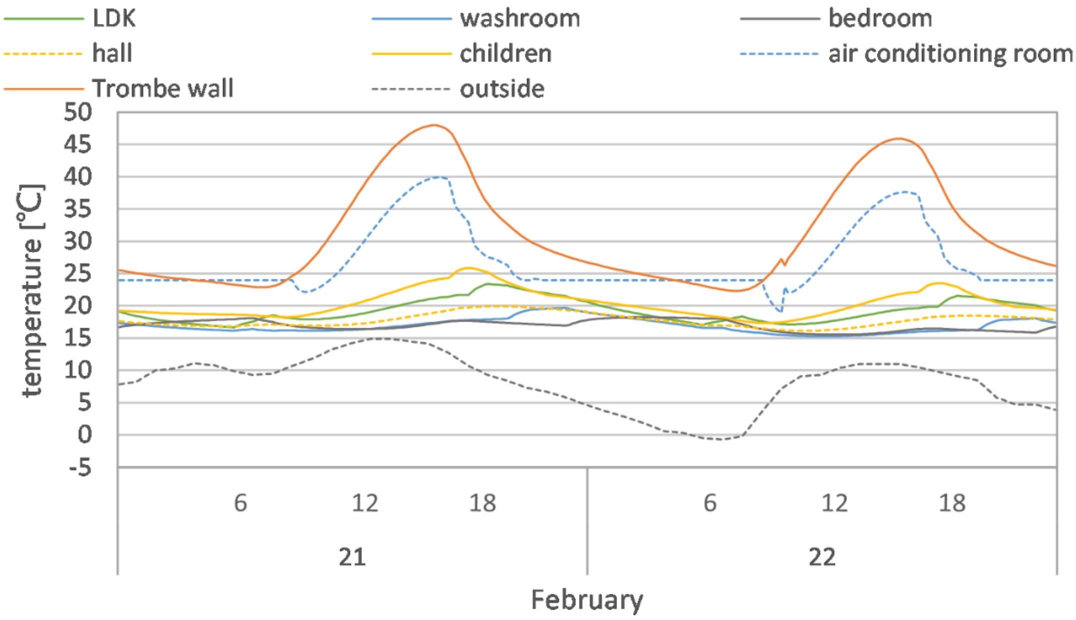

Figure 7.24 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.8. Thermal environment of Model VI (the Trombe wall on the first and second floors)

Figure 7.25 shows the temperature fluctuation of each room in all-day air conditioning. In all air conditioning methods, the temperature of the first floor Trombe wall is lower than the temperature of the second floor Trombe wall. The air inside the Trombe wall on the second floor is sent to the air conditioning room, and the air in the air conditioning room is sent to the Trombe wall on the first floor. Since there is air movement between the first floor Trombe wall and second floor Trombe wall, it can be said that as the warm air moves upwards, the temperature of the second floor Trombe wall is higher. On the morning of February 22, the outdoor temperature was lower than 0°C. The temperature in each room is always maintained above 20 °C.

In the case of all-day air conditioning, the central air conditioning room temperature rose due to the air circulation between in the Trombe wall and the central air conditioning room. Even if the heat was sent from the Trombe wall to the central air conditioning room, the Trombe wall temperature increased. It can be said that the heat inside the Trombe wall is sufficient. In addition, although the heat is sent from the Trombe wall to the central air conditioning room, the temperature inside the Trombe wall is kept high. The maximum temperature of the Trombe wall is about 15 °C higher than the Trombe wall of model V. It can be said that the temperature inside the Trombe wall increases as the volume of the Trombe wall increases.

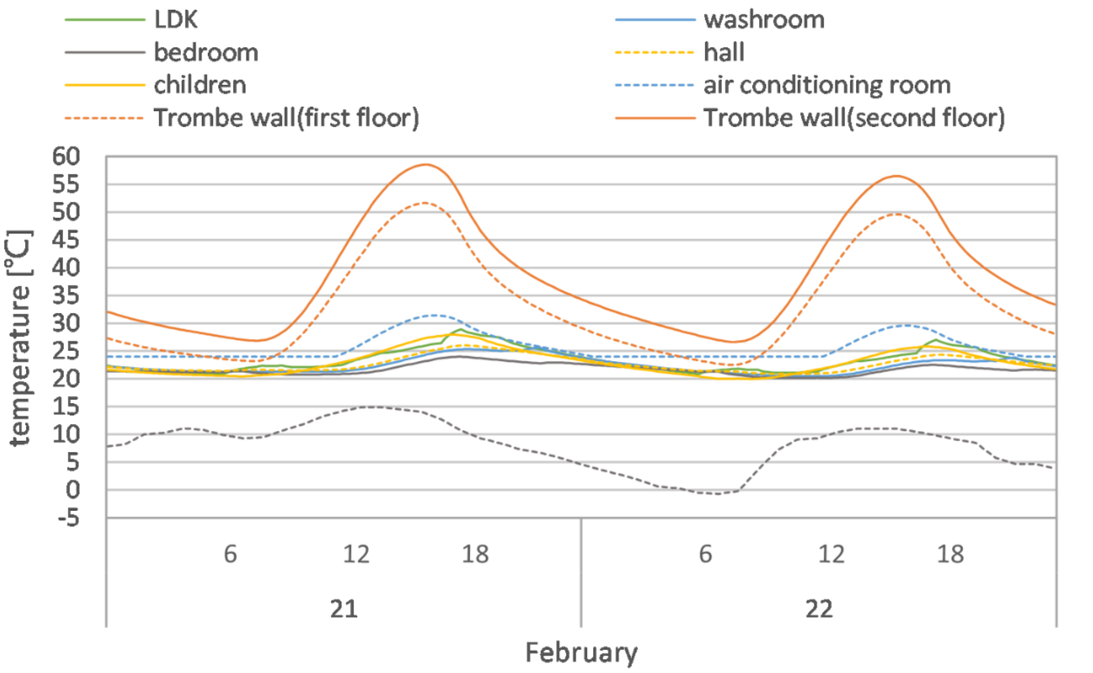

Figure 7.25 The temperature fluctuation of each room in all-day air conditioning

Figure 7.26 shows the temperature fluctuation of each room in intermittent air conditioning. In the case of intermittent air conditioning, after the central air conditioning was turned off, it was found that the temperature of the central air conditioning room rose after the Trombe wall temperature reached 26 °C. At this time, the air flow from the air conditioning room to each room is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. Even if the central air conditioning is turned off, the temperature in most of rooms is above 20°C for most of the time on February 21, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. At 18 o'clock, the air was sent from the central air conditioning room to the children's room and LDK, and the temperature of the air conditioning room dropped sharply. The amount of air sent to the children's room was 560 m^3/h, and the amount of air sent to LDK was 840 m^3/h. It can be said that the heat in central air conditioning rooms is used excessively.

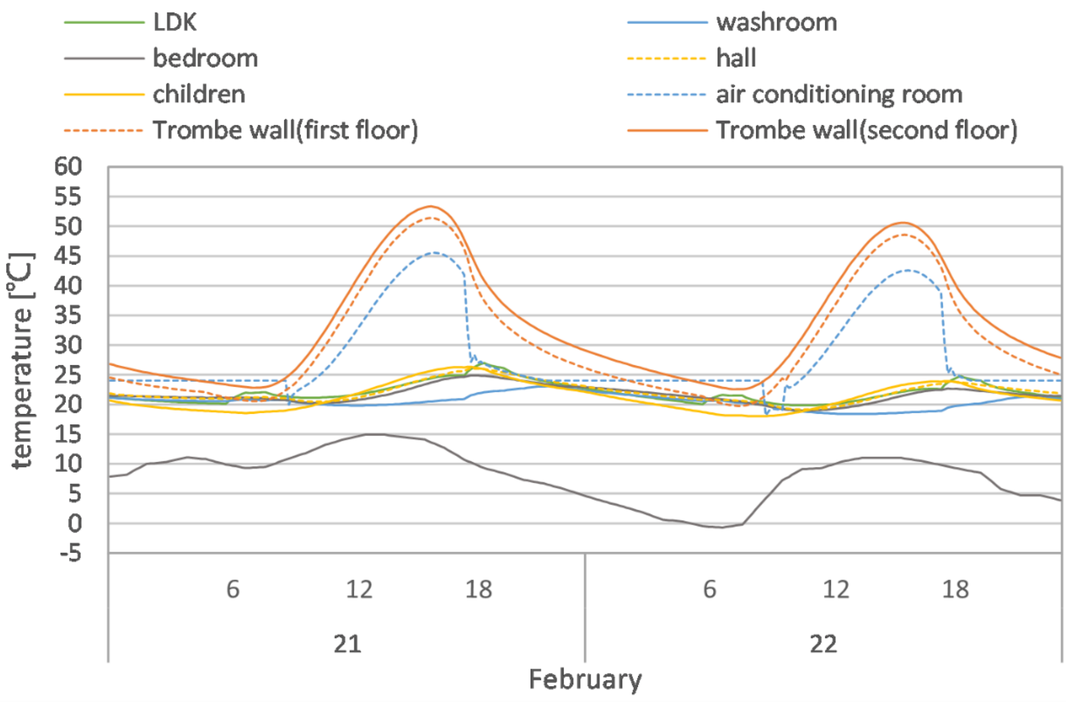

Figure 7.26 The temperature fluctuation of each room in intermittent air conditioning

Figure 7.27 shows the temperature fluctuation of each room in intermittent individual room air conditioning (housewife). In the case of intermittent individual room air conditioning (housewife), the central air conditioning room temperature fluctuates due to air circulation between the LDK and the central air conditioning room and intermittent air conditioning. With the exception of the LDK, the air flow from the air conditioning room to each other rooms is only the necessary ventilation. The central air conditioning's heat cannot be fully utilized. In the case of intermittent individual room air conditioning (housewife), the time for central air conditioning to be turned off is shortened. Therefore, the temperature of the LDK does not drop when the central air conditioning is turned off. In addition, due to the increase of the outside air temperature and the air circulation between the central air conditioning room and LDK, the comfort temperature of the LDK during the day has been reached. The LDK temperature dropped in the morning because the central air conditioning system was shut down from 23 o'clock. The air was sent to the children's room from 18:00 to 7:00, but the temperature of the children's room decreased as the outside temperature dropped, and was below 20 °C from 3 o'clock. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is above 20 °C. It is possible to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. Most of the time the washroom temperature was above 20 °C during bathing. The washroom temperature was below 20 °C in other times. The temperature difference between the washroom and the LDK may be close to 8 °C. By opening the door between the LDK and the washroom throughout the day, the LDK can be prevented from overheating and the temperature of the washroom can be raised to create a comfortable thermal environment.

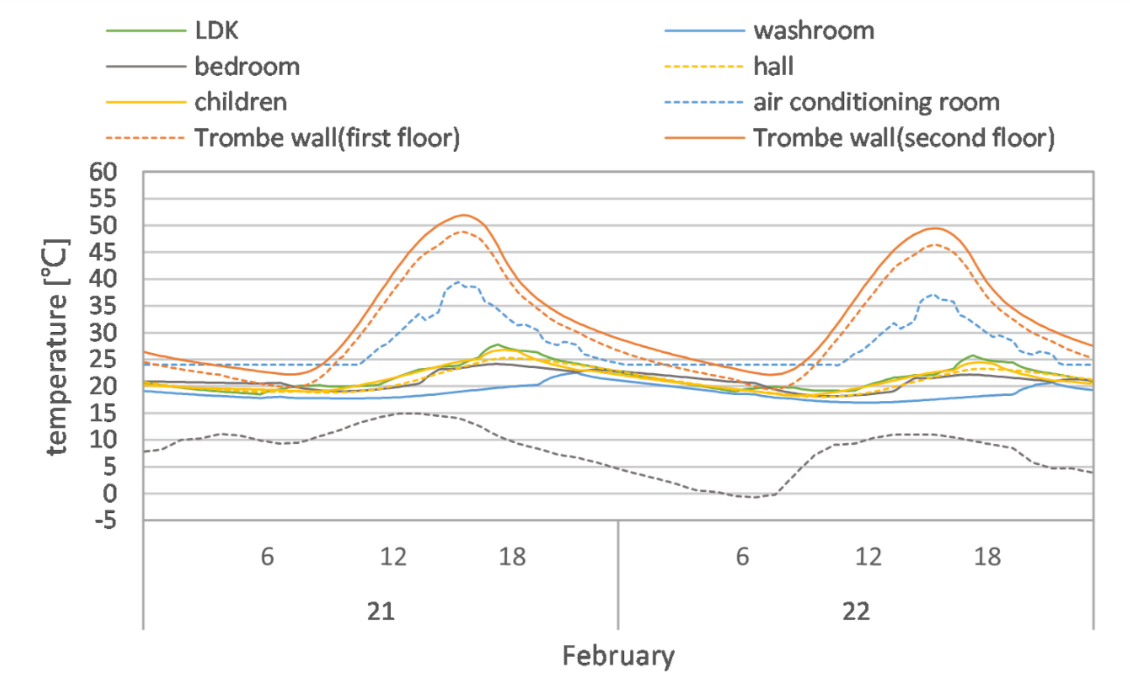

Figure 7.27 The temperature fluctuation of each room in intermittent individual room air conditioning (housewife)

Figure 7.28 shows the temperature fluctuation of each room in intermittent individual room air conditioning (worker). In the case of intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the Trombe wall and the central air conditioning room. The temperature of the central air conditioning room rose to about 49 °C. Therefore, it is possible to reduce the ratio of the temperature below 20 °C during the nighttime by sending the heat from the Trombe wall to rooms that are not used during the daytime. The air circulation between the LDK and the central air conditioning is turned on from 7:00 to 8:00 and from 18:00 to 23:00. Since the air circulation is only turned on at 7:00 to 8:00 in the morning, it is difficult to increase the temperature of the LDK that has been lowered at night, so the LDK temperature in the morning is uncomfortable. The LDK temperature rises with the increase of the outside temperature during the daytime and decreases with the decrease of the outside temperature during the nighttime. The air circulation from 18 o'clock and 23 o'clock can maintain a comfortable temperature for LDK. The air circulation between the children's room and the central air conditioning is switched on from 18:00 to 7:00. However, the temperature of the children's room decreased as the outdoor temperature decreased, and was below 20 °C for 3 o'clock. The air circulation between the bedroom and the central air conditioning is turned on from 22 o'clock to 7 o'clock. At all times, the bedroom temperature is below 20 °C. It is difficult to keep comfortable temperature for bedroom. The air circulation between the washroom and the central air conditioning is turned on only during bathing. On the 21st, the washroom temperature exceeded 20°C, but it was less than 20°C on the 22nd.

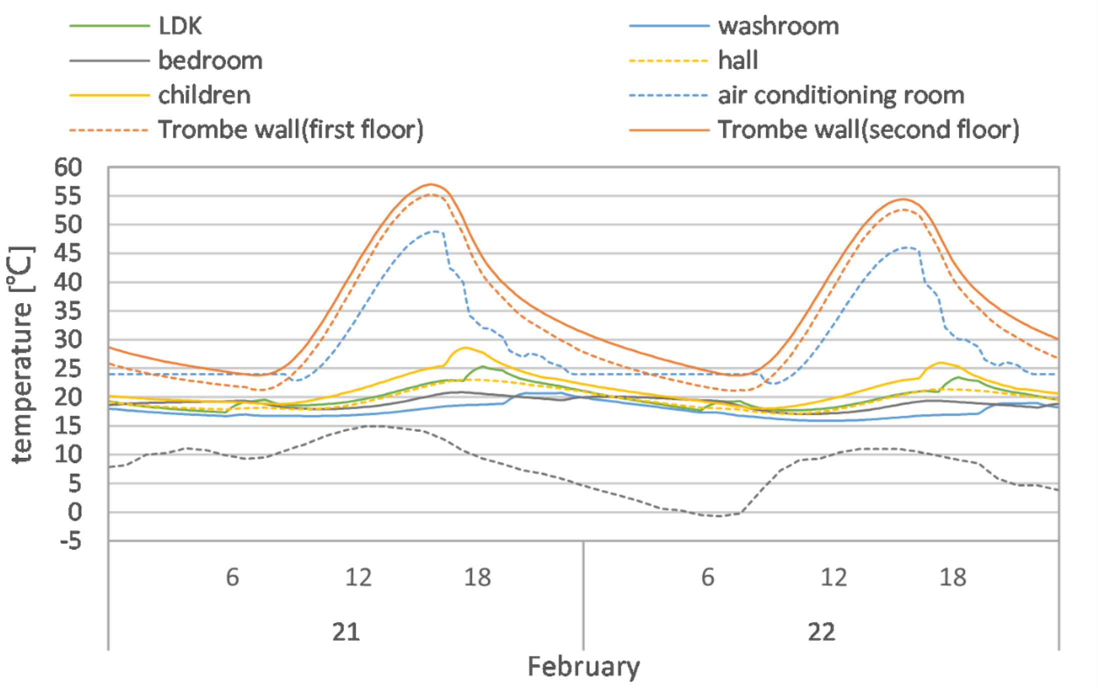

Figure 7.28 The temperature fluctuation of each room in intermittent individual room air conditioning (worker)

7.9. Comparison of each room temperature (sunspace)

Table 7.1 shows the calculation cases. Figures 7.29 to 7.35 show the temperature fluctuation of LDK, children's room, bedroom, central air conditioning room, sunspace, washroom, and hall, respectively.

Table 7.1 Calculation cases

Model	Air conditioning method	Life style	Case
Model Io	All-day air conditioning	housewife	a
	Intermittent air conditioning	worker	b
	Intermittent individual room air conditioning	housewife	c
		worker	d
Model I	All-day air conditioning	housewife	e
	Intermittent air conditioning	worker	f
	Intermittent individual room air conditioning	housewife	g

		worker	h
Model II	All-day air conditioning	housewife	i
	Intermittent air conditioning	worker	j
	Intermittent individual room air conditioning	housewife	k
		worker	l

In Cases a, e and i (all-day air conditioning), the LDK room temperature is comfortable (above 20 °C). In Cases b, f and j (intermittent air conditioning), the LDK room temperature is comfortable (above 20 °C). In Cases c, d, g, h, k and l (intermittent individual room air conditioning), the LDK room temperature is uncomfortable (below 20 °C).

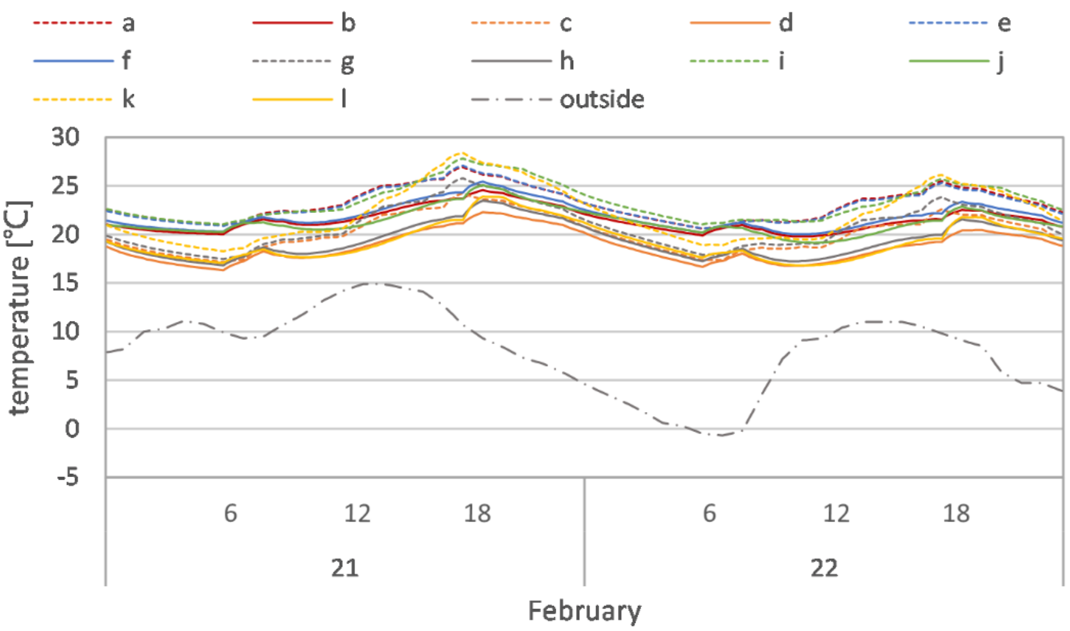

Figure 7.29 The LDK temperature fluctuation

In Case i (all-day air conditioning), the children’s room temperature is comfortable (above 20 °C). In other cases, there is a time period below 20 °C in the children's room temperature.

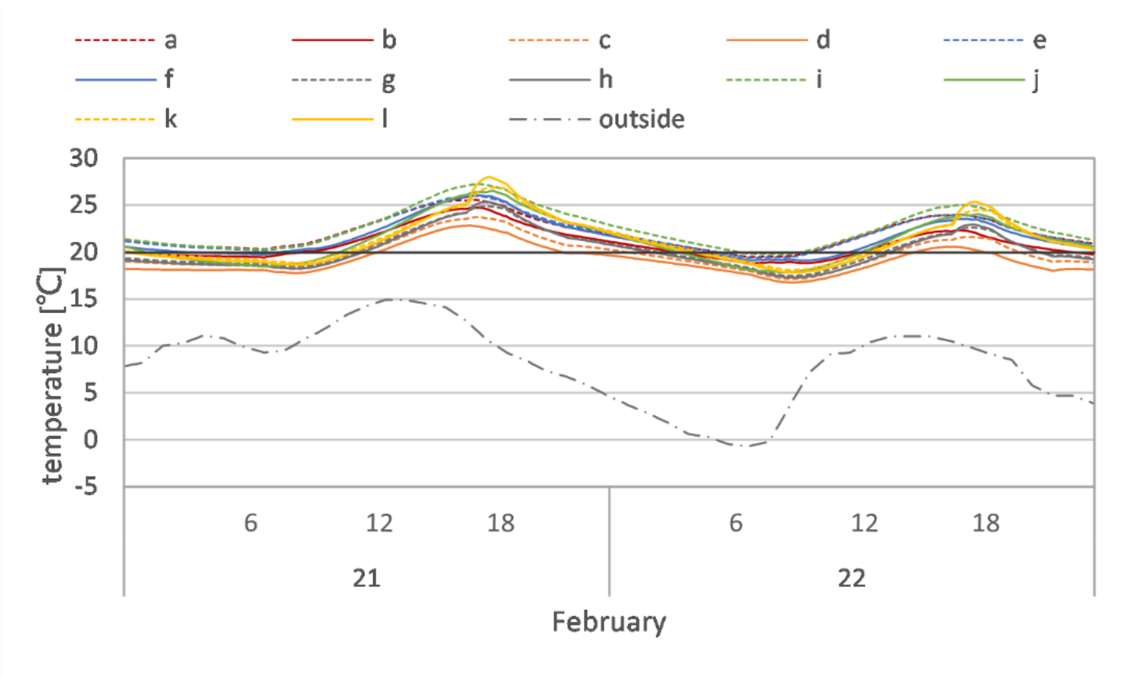

Figure 7.30 The children's room temperature fluctuation

In Cases a, e and i (all-day air conditioning), the bedroom temperature is comfortable (above 20 °C). In Case j (intermittent air conditioning), the bedroom room temperature is comfortable (above 20 °C). In other cases, there is a time period below 20 °C in the bedroom temperature.

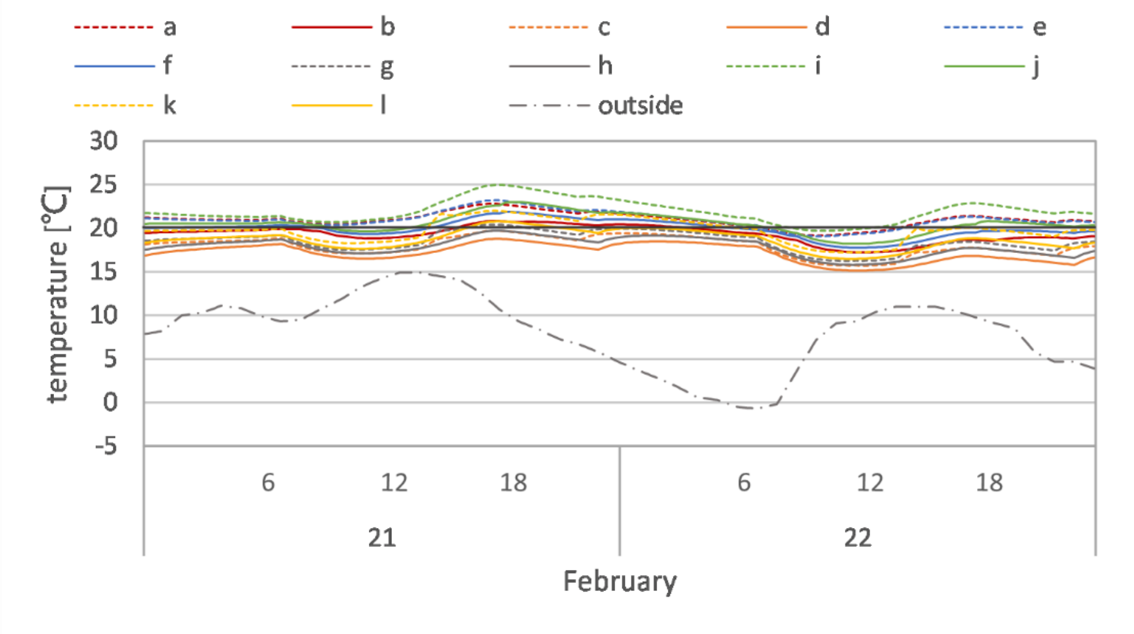

Figure 7.31 The bedroom temperature fluctuation

The temperature of the central air conditioning room rose by sending air from the sunspace to the central air conditioning room. The proportion of the central air conditioning room temperature exceeding 24°C was prolonged by increasing the capacity of the sunspace.

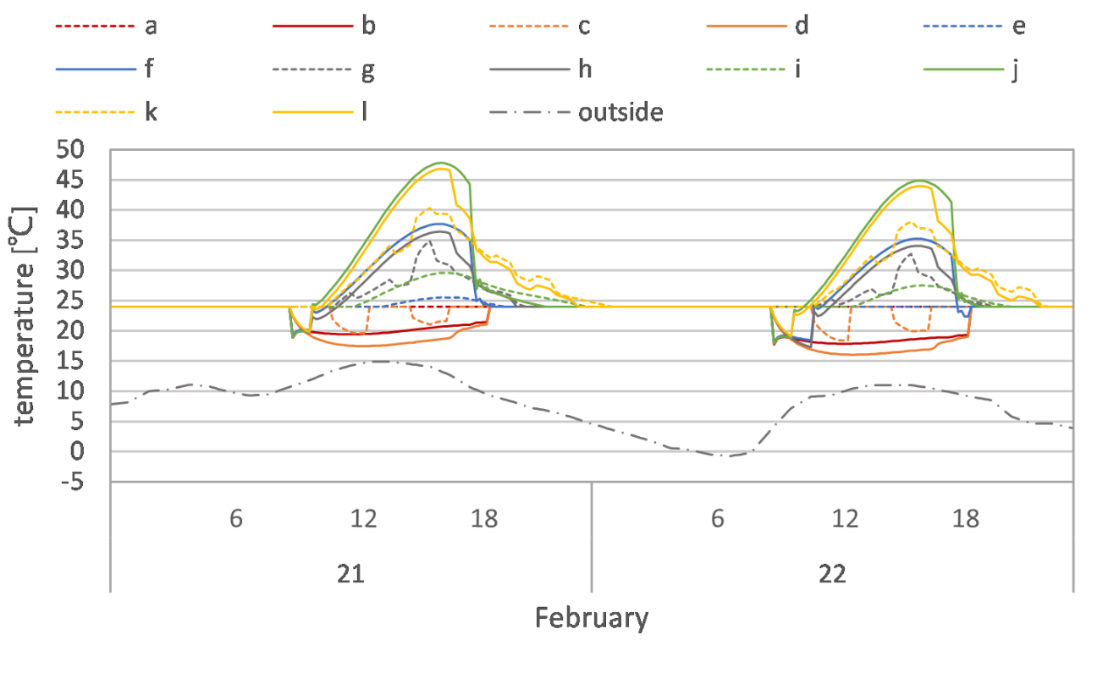

Figure 7.32 The central air conditioning room temperature fluctuation

The sunspace temperature rose by increasing the capacity of the sunspace. The proportion of the sunspace temperature exceeding 26°C was prolonged by increasing the capacity of the sunspace.

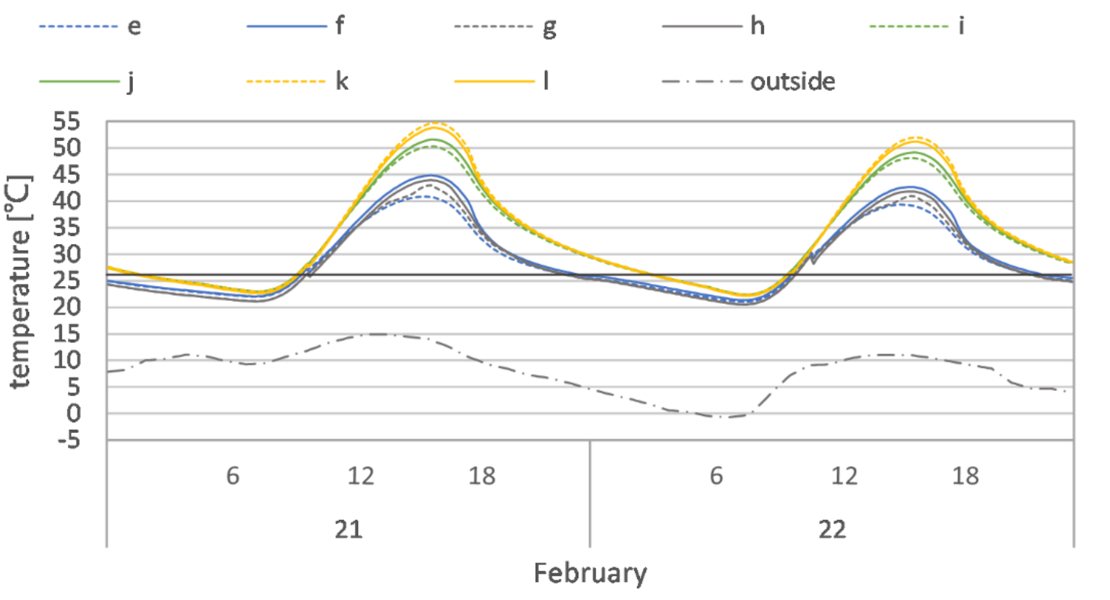

Figure 7.33 The sunspace temperature fluctuation

In Cases a, e and i (all-day air conditioning), the washroom temperature is comfortable (above 20 °C). In Cases b, f and j (intermittent air conditioning), although the temperature of the washroom drops during the daytime, but the temperature of the washroom approaches the comfort temperature as the outside air temperature rises.

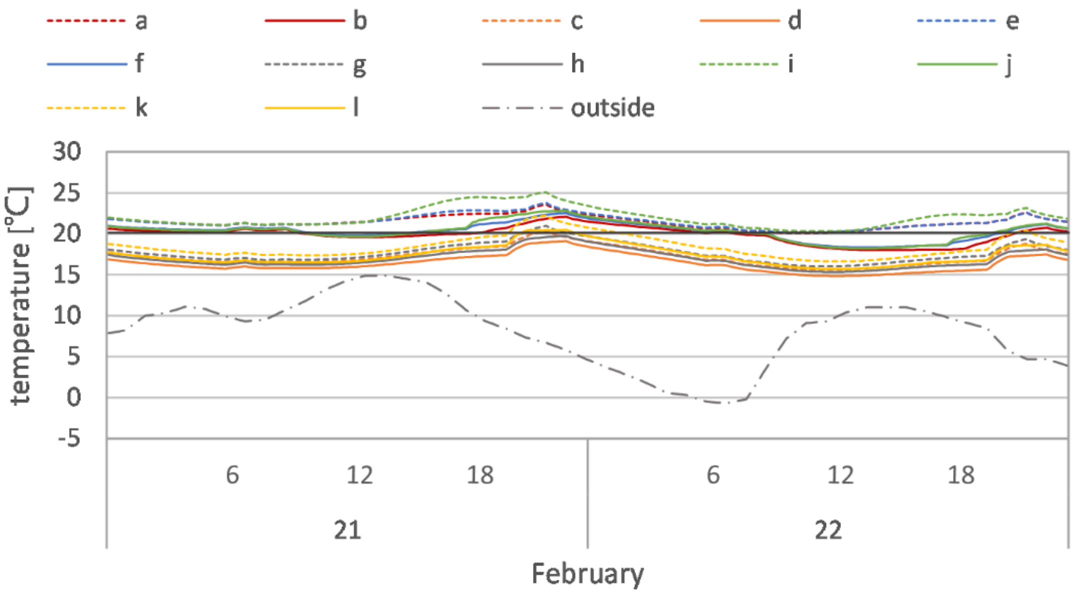

Figure 7.34 The washroom temperature fluctuation

In Cases a, e and i (all-day air conditioning), the hall temperature is comfortable (above 20 °C). In Cases b, f and j (intermittent air conditioning), although the temperature of the hall drops during the daytime, but the temperature of the hall approaches the comfort temperature as the outside air temperature rises.

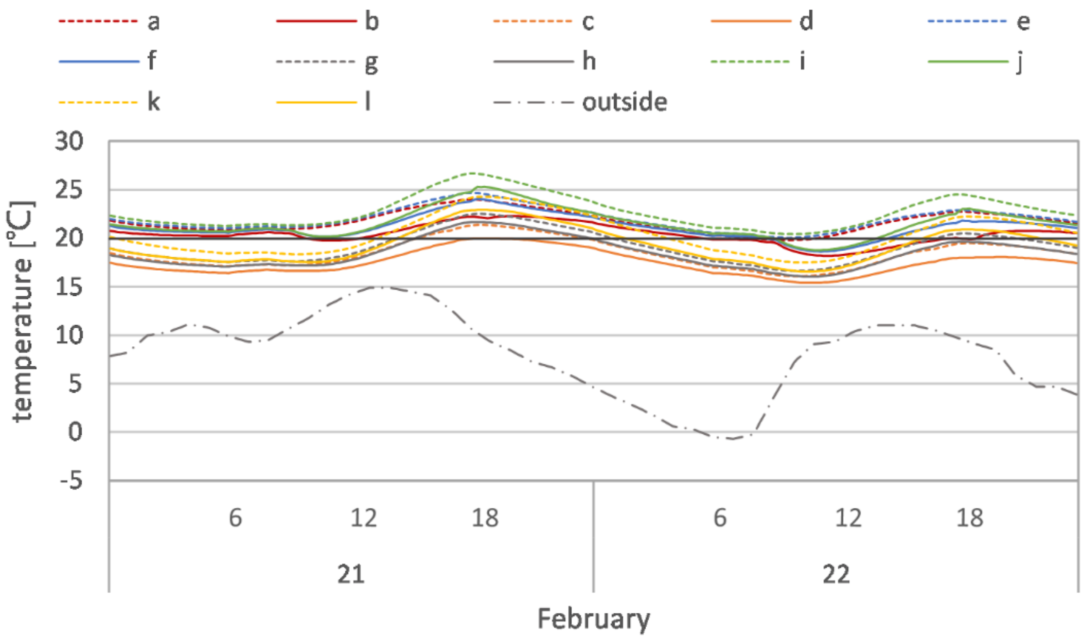

Figure 7.35 The hall temperature fluctuation

Therefore, in the case of all-day air conditioning, the central air conditioning system can maintain a comfortable temperature for each room. In the case of intermittent air conditioning, the central air conditioning system can maintain a comfortable temperature for most rooms. In the case of intermittent individual room air conditioning, the central air conditioning system cannot maintain a comfortable temperature from midnight to morning. In the case of intermittent individual room air conditioning, the sunspace temperature is very high and the heat is not fully utilized. Therefore, the period of comfort temperature can be extended by increasing the amount of ventilation to the bedroom, washroom and hall.

7.10. Comparison of each room temperature (double skin facade)

Table 7.2 shows the calculation cases. Figures 7.36 to 7.42 show the temperature fluctuation of LDK, children's room, bedroom, central air conditioning room, sunspace, washroom, and hall, respectively.

Table 7.2 Calculation cases

Model	Air conditioning method	Life style	Case
Model III	All-day air conditioning	housewife	D-e
	Intermittent air conditioning	worker	D-f
	Intermittent individual room air conditioning	housewife	D-g
		worker	D-h

Model IV	All-day air conditioning	housewife	D-i
	Intermittent air conditioning	worker	D-j
	Intermittent individual room air conditioning	housewife	D-k
		worker	D-l

In Cases D-e and D-i (all-day air conditioning), the LDK room temperature is comfortable (above 20 °C). In Cases D-f and D-j (intermittent air conditioning), the LDK room temperature is comfortable (above 20 °C). In Cases D-g, D-h, D-k and D-l (intermittent individual room air conditioning), the LDK room temperature is uncomfortable (below 20 °C).

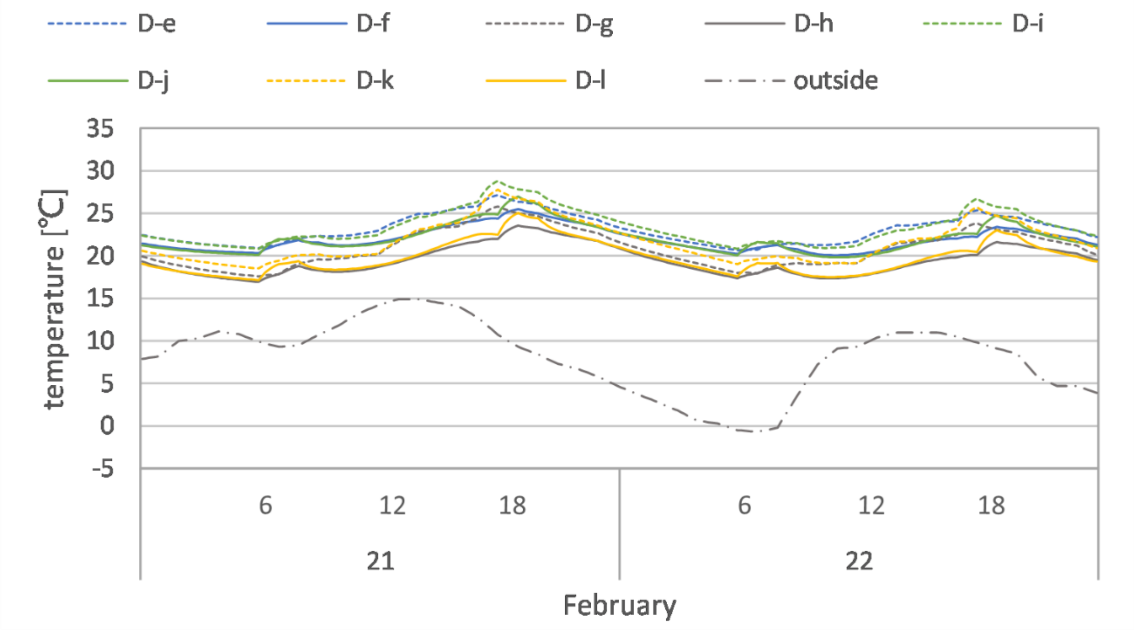

Figure 7.36 The LDK temperature fluctuation

In Cases D-e and D-i (all-day air conditioning), the children’s room temperature is comfortable (above 20 °C). In other cases, there is a time period below 20 °C in the children's room temperature.

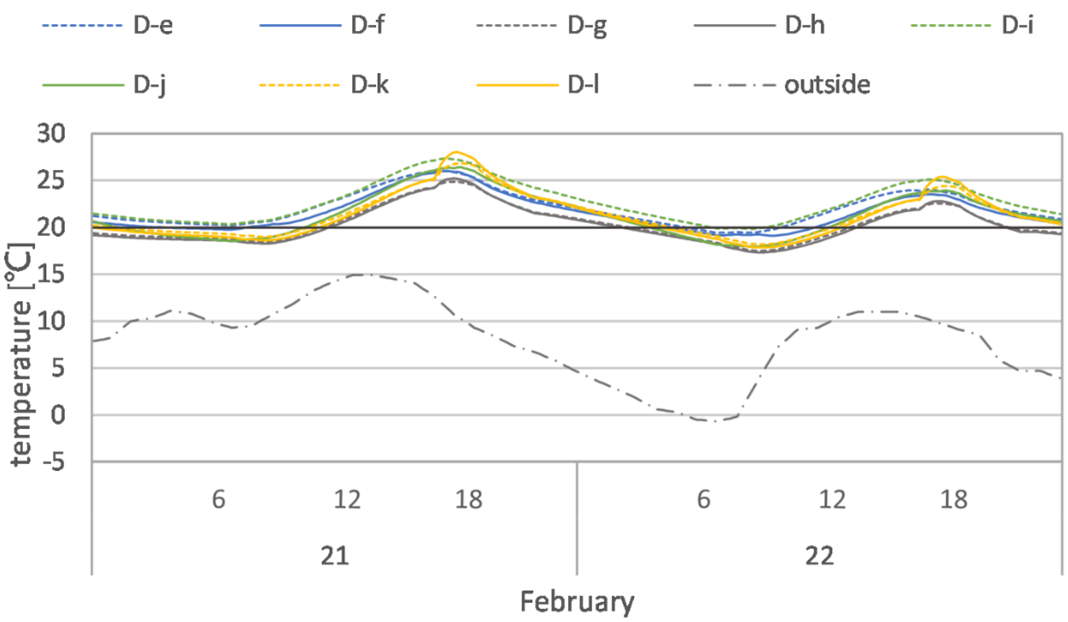

Figure 7.37 The children's room temperature fluctuation

In Cases D-e and D-i (all-day air conditioning), the bedroom temperature is comfortable (above 20 °C). In Cases D-f and D-j (intermittent air conditioning), the bedroom room temperature is comfortable (above 20 °C). In Case D-k (intermittent individual room air conditioning), the bedroom room temperature is comfortable (above 20 °C). In other cases, there is a time period below 20 °C in the bedroom temperature.

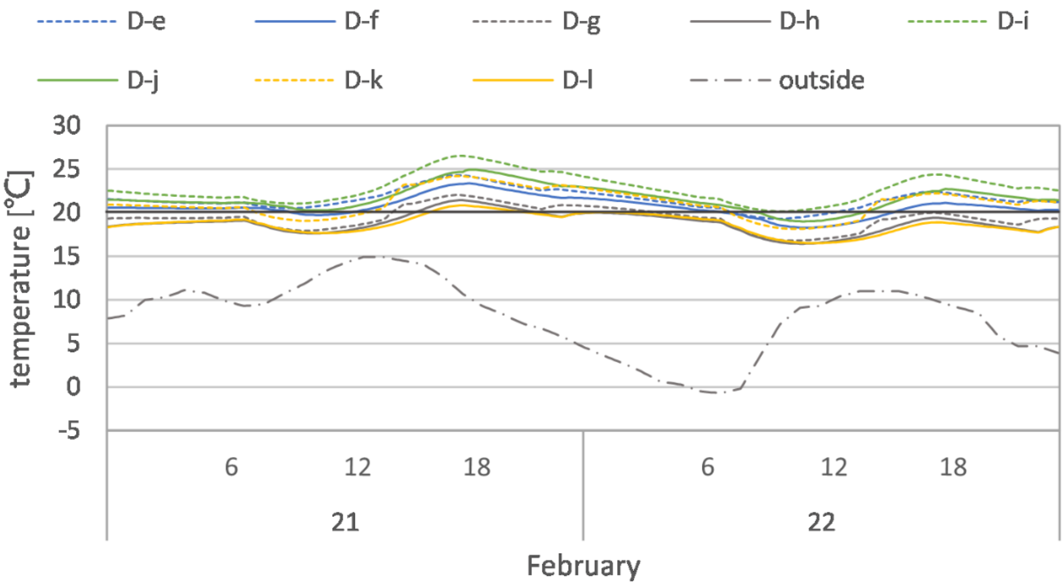

Figure 7.38 The bedroom temperature fluctuation

The temperature of the central air conditioning room rose by sending air from the double skin facade to the central air conditioning room. The proportion of the central air conditioning room temperature exceeding 24°C was prolonged by increasing the capacity of the sunspace.

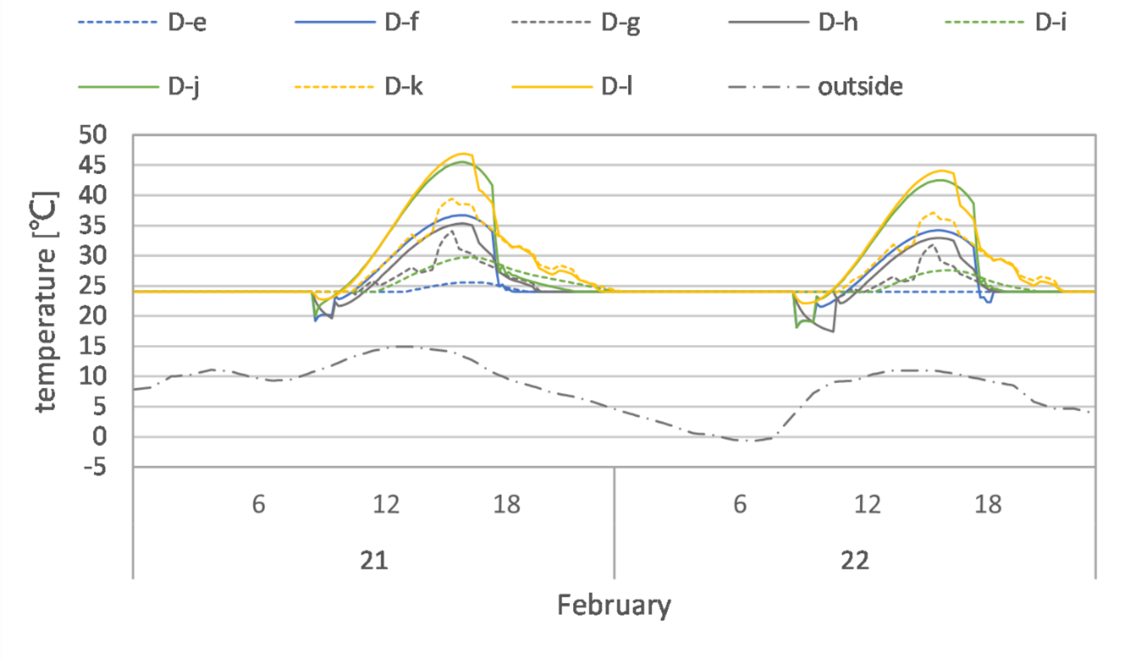

Figure 7.39 The central air conditioning room temperature fluctuation

The double skin facade temperature rose by increasing the capacity of the double skin facade. The proportion of the double skin facade temperature exceeding 26°C was prolonged by increasing the capacity of the sunspace.

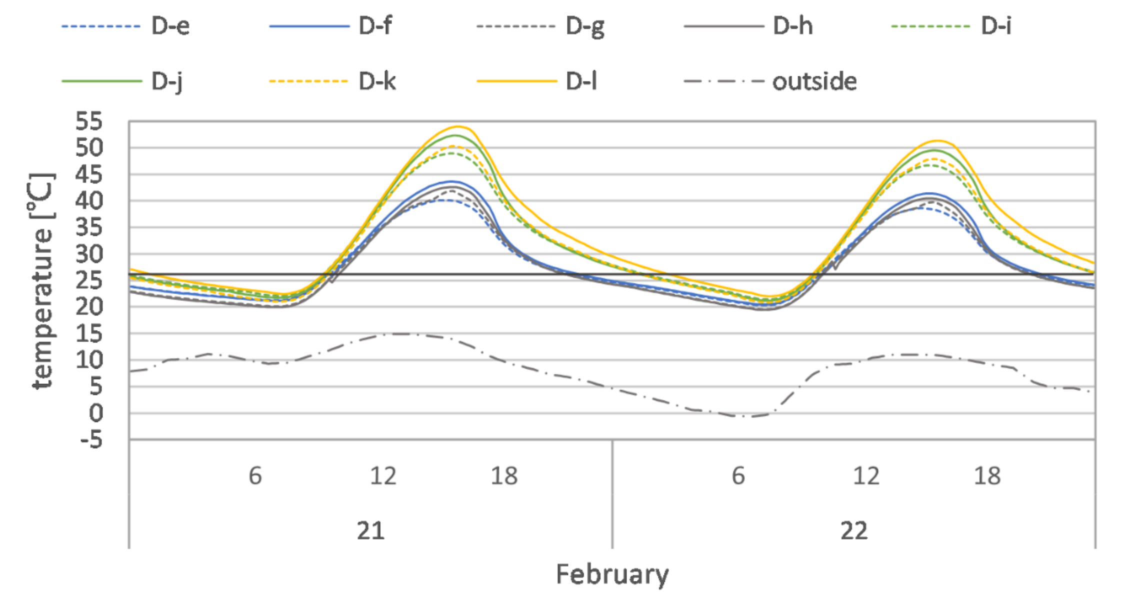

Figure 7.40 The double skin facade temperature fluctuation

In Cases D-e and D-i (all-day air conditioning), the washroom temperature is comfortable (above 20 °C). In Cases D-f and D-j (intermittent air conditioning), although the temperature of the washroom drops during the daytime, but the temperature of the washroom approaches the comfort temperature as the outside air temperature rises. In Case D-k (intermittent individual room air conditioning), the washroom temperature approached the comfort temperature during bathing.

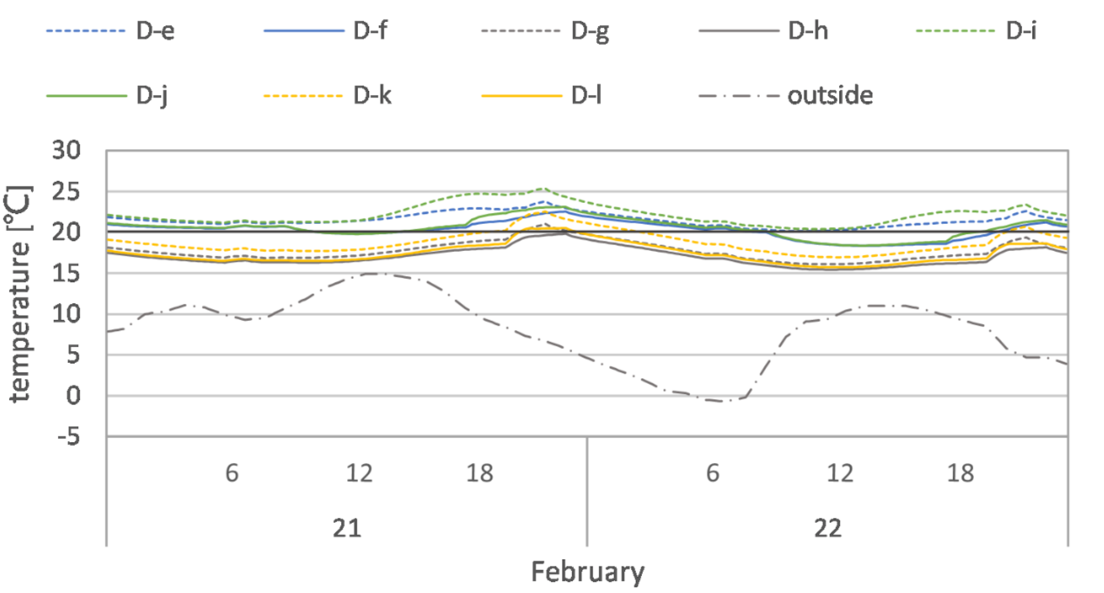

Figure 7.41 The washroom temperature fluctuation

In Cases e and i (all-day air conditioning), the hall temperature is comfortable (above 20 °C). In Cases f and j (intermittent air conditioning), although the temperature of the hall drops during the daytime, but the temperature of the hall approaches the comfort temperature as the outside air temperature rises.

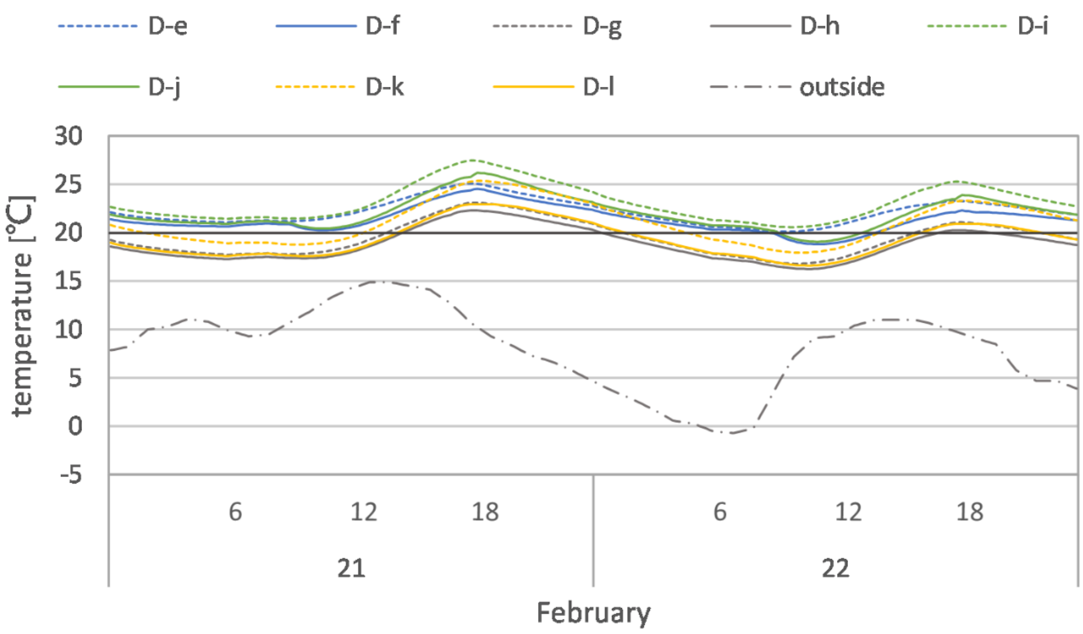

Figure 7.42 The hall temperature fluctuation

Therefore, in the case of all-day air conditioning, the central air conditioning system can maintain a comfortable temperature for each room. In the case of intermittent air conditioning, the central air conditioning system can maintain a comfortable temperature for most rooms. In the case of intermittent individual room air conditioning, the central air conditioning system cannot maintain a comfortable temperature from midnight to morning. In the case of intermittent individual room air conditioning, the double skin facade temperature is very high and the heat is not fully utilized. Therefore, the period of comfort temperature can be extended by increasing the amount of ventilation to the bedroom, washroom and hall.

7.11. Comparison of each room temperature (Trombe wall)

Table 7.1 shows the calculation cases. Figures 7.43 to 7.49 show the temperature fluctuation of LDK, children's room, bedroom, central air conditioning room, sunspace, washroom, and hall, respectively.

Table 7.3 Calculation cases

Model	Air conditioning method	Life style	Case
	All-day air conditioning	housewife	T-e
Model V	Intermittent air conditioning	worker	T-f
	Intermittent individual room air conditioning	housewife	T-g

		worker	T-h
Model VI	All-day air conditioning	housewife	T-i
	Intermittent air conditioning	worker	T-j
	Intermittent individual room air conditioning	housewife	T-k
		worker	T-l

In Cases T-e and T-i (all-day air conditioning), the LDK room temperature is comfortable (above 20 °C). In Cases f and T-j (intermittent air conditioning), the LDK room temperature is comfortable (above 20 °C). In Cases T-d, T-g, T-h, T-k and T-l (intermittent individual room air conditioning), the LDK room temperature is uncomfortable (below 20 °C).

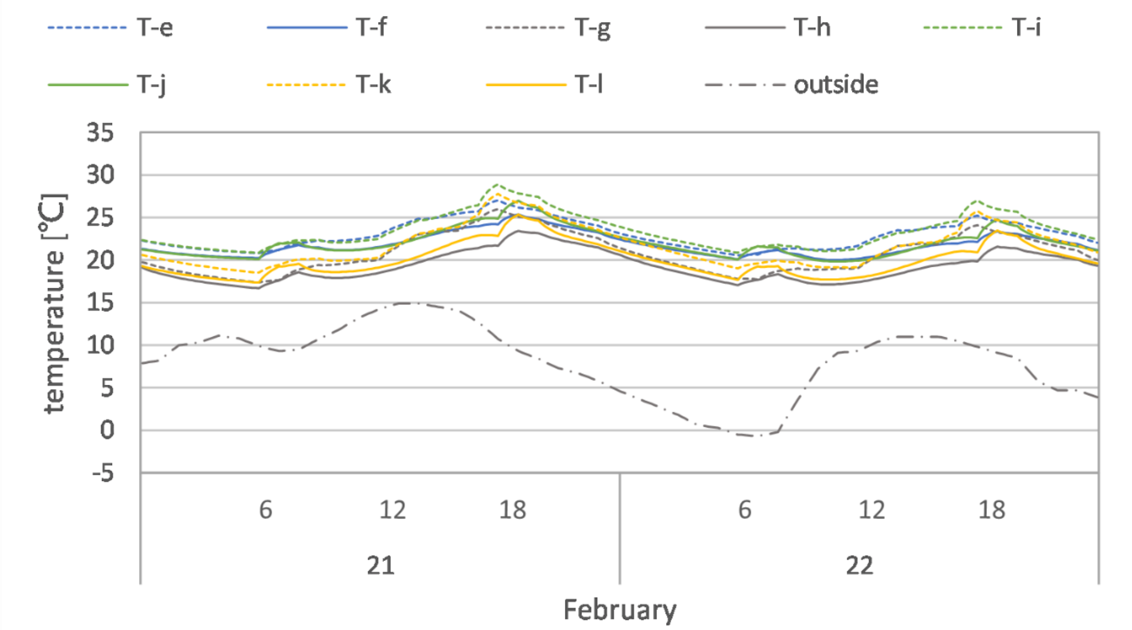

Figure 7.43 The LDK temperature fluctuation

In Cases T-e and T-i (all-day air conditioning), the children’s room temperature is comfortable (above 20 °C). In other cases, there is a time period below 20 °C in the children's room temperature.

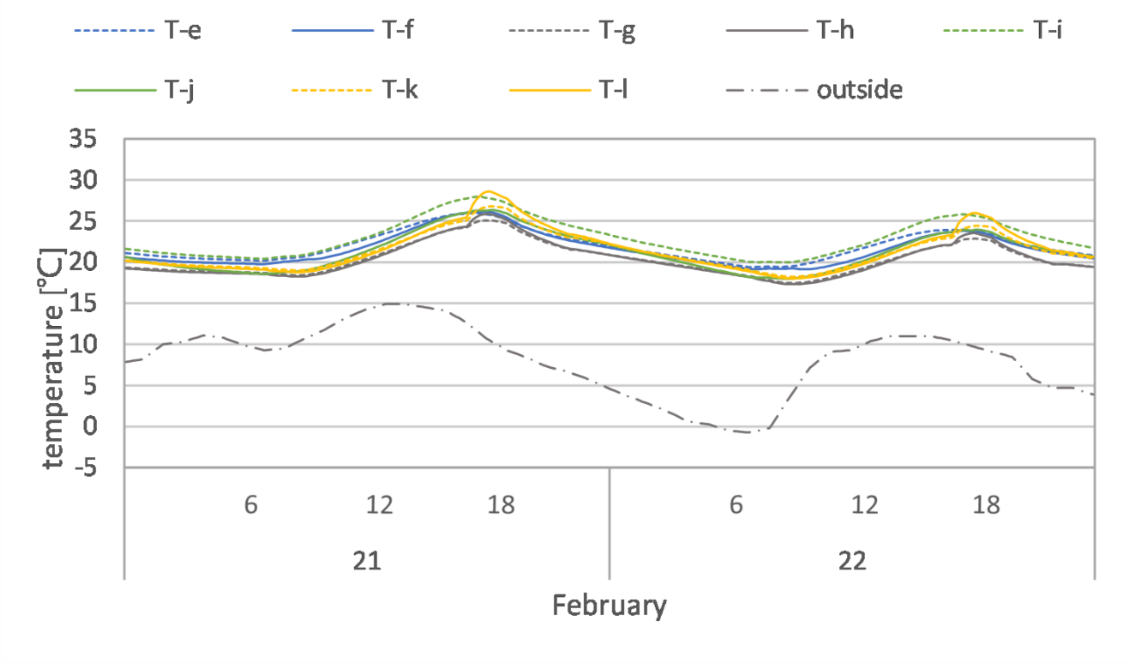

Figure 7.44 The children's room temperature fluctuation

In Cases T-e and T-i (all-day air conditioning), the bedroom temperature is comfortable (above 20 °C). In Case T-j (intermittent air conditioning), the bedroom room temperature is comfortable (above 20 °C). In Case T-k (intermittent individual room air conditioning), the bedroom room temperature is comfortable (above 20 °C). In other cases, there is a time period below 20 °C in the bedroom temperature.

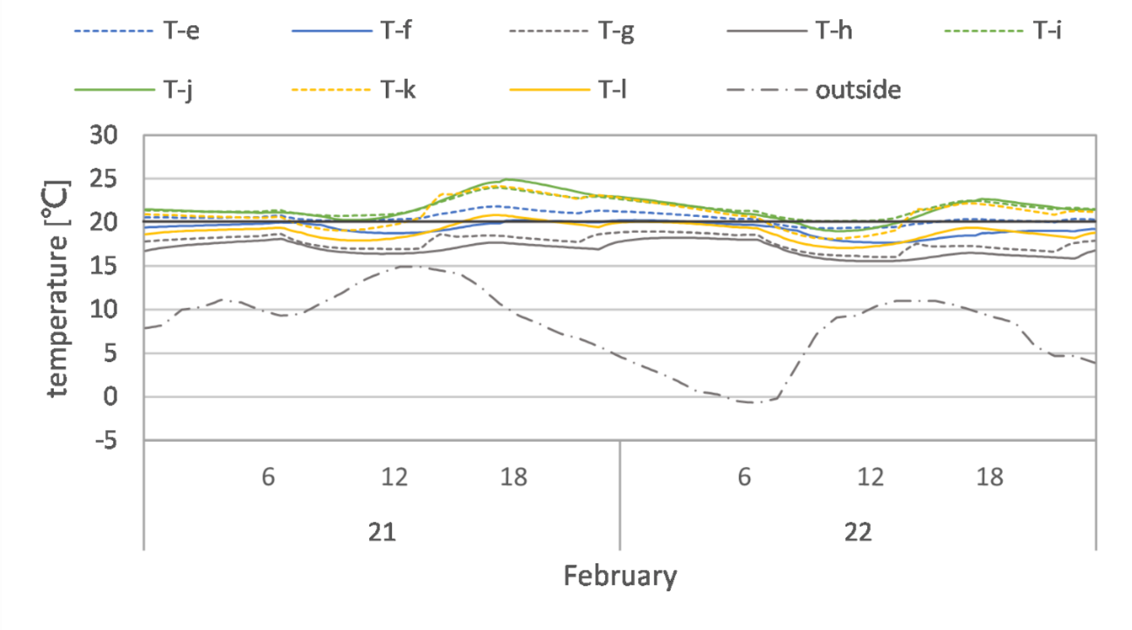

Figure 7.45 The bedroom temperature fluctuation

The temperature of the central air conditioning room rose by sending air from the Trombe wall to the central air conditioning room. The proportion of the central air conditioning room temperature exceeding 24°C was prolonged by increasing the capacity of the Trombe wall.

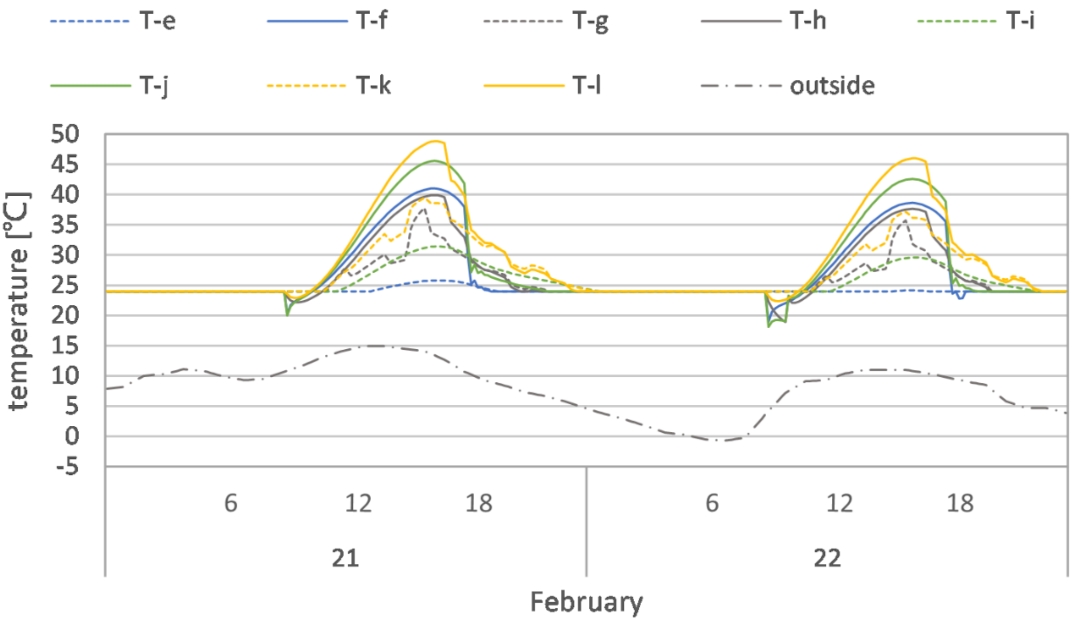

Figure 7.46 The central air conditioning room temperature fluctuation

The Trombe wall temperature rose by increasing the capacity of the Trombe wall. The proportion of the Trombe wall temperature exceeding 26°C was prolonged by increasing the capacity of the Trombe wall.

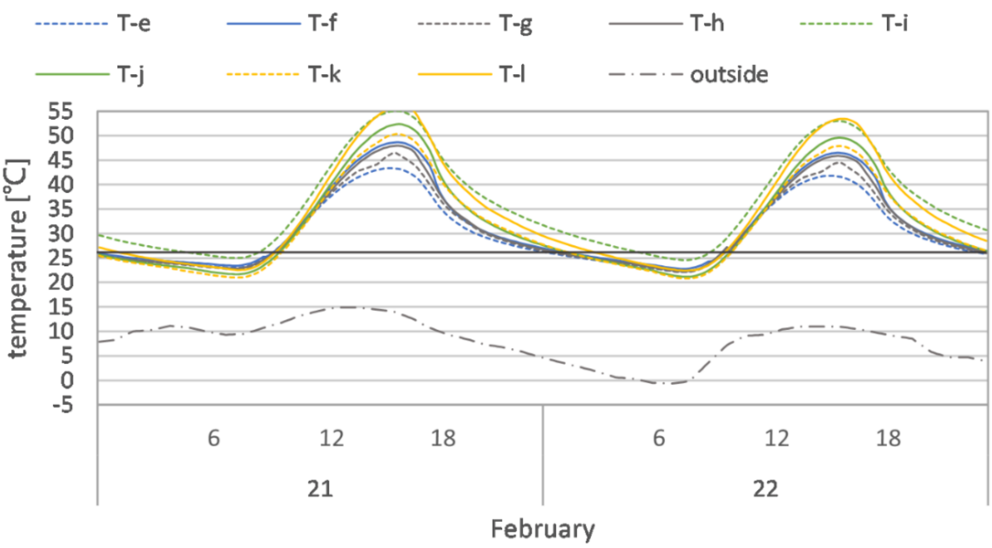

Figure 7.47 The Trombe wall temperature fluctuation

In Cases e and i (all-day air conditioning), the washroom temperature is comfortable (above 20 °C). In Cases f and j (intermittent air conditioning), although the temperature of the washroom drops during the daytime, but the temperature of the washroom approaches the comfort temperature as the outside air temperature rises. In Case T-k (intermittent individual room air conditioning), the washroom temperature approached the comfort temperature during bathing.

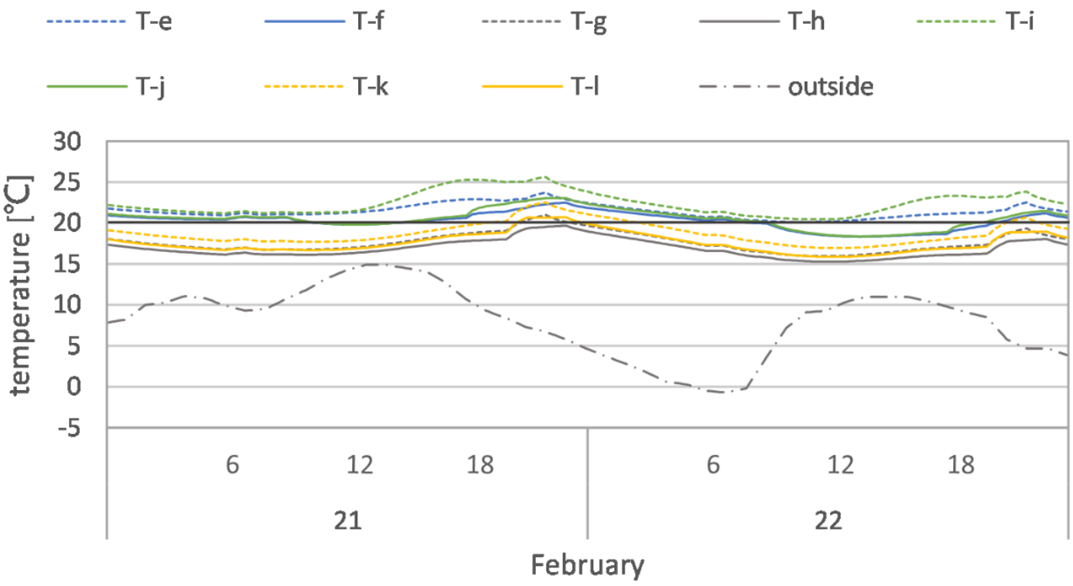

Figure 7.48 The washroom temperature fluctuation

In Cases a, e and i (all-day air conditioning), the hall temperature is comfortable (above 20 °C). In Cases b, f and j (intermittent air conditioning), although the temperature of the hall drops during the daytime, but the temperature of the hall approaches the comfort temperature as the outside air temperature rises.

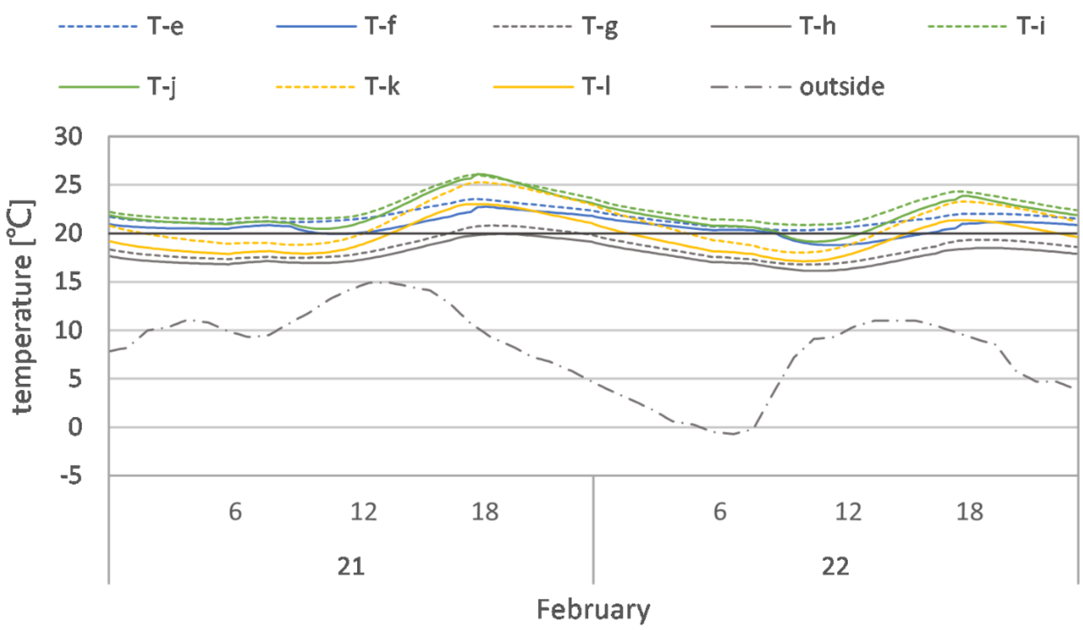

Figure 7.49 The hall temperature fluctuation

Therefore, in the case of all-day air conditioning, the central air conditioning system can maintain a comfortable temperature for each room. In the case of intermittent air conditioning, the central air conditioning system can maintain a comfortable temperature for most rooms. In the case of intermittent individual room air conditioning, the central air conditioning system cannot maintain a comfortable temperature from midnight to morning. In the case of intermittent individual room air conditioning, the Trombe wall temperature is very high and the heat is not fully utilized. Therefore, the period of comfort temperature can be extended by increasing the amount of ventilation to the bedroom, washroom and hall.

7.12. Summary

In this chapter, based on numerical simulation, the thermal environment of each room was studied. The results were as follows:

In the case of Model Io with all-day air conditioning, even though the outdoor temperature was below 0°C, most of the time, the temperature of the LDK, washroom, washroom and hall was kept above 20°C. Therefore, the central air conditioning system can effectively maintain a comfortable temperature for most rooms. In addition, since the temperature difference in each room is within 5°C, it can be said that the central air conditioning system can effectively prevent heat shock.

In the case of Model Io with intermittent air conditioning, the central air conditioning system is turned off during the daytime, the temperature of the washroom, bedroom and central air conditioning system room is below 20°C. When the central air conditioning system is turned on, the temperature of each room is maintained at 20°C or more for most of the time. Due to solar radiation, the temperature of the children's room and the LDK room in the south is higher than other rooms during the daytime. Although the bedroom faces south, due to the influence of the side walls and roof of the balcony, the temperature of the bedroom is barely affected by solar radiation.

In the case of Model Io with intermittent individual room air conditioning, it is difficult to increase the temperature of each room that has been lowered at night. As a result, it is difficult to maintain the comfort temperature of each room.

In the case of Models I, III and V with all-day air conditioning, even if the heat is sent from the air cavity (sunspace, DSF and Trombe wall) to the central air conditioning room, the air cavity (sunspace, DSF and Trombe wall) temperature does not decrease and maintains high temperature.

In the case of Models I, II, III, IV, V and VI with intermittent air conditioning, even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C.

In the case of Models I, II, III, IV, V and VI with intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the air cavity (sunspace, DSF and Trombe wall) and the central air conditioning room. Therefore, it is possible to reduce the ratio of the temperature below 20°C during the nighttime by sending the heat from the air cavity (sunspace, DSF and Trombe wall) to rooms that are not used during the daytime.

Chapter 8.

Conclusions

8. Conclusions

In the thesis, we conducted an actual survey to understand the situation of heat utilization of the air channel and used numerical simulations to examine the effective method of heat utilization of the air channel. To reduce the heating load, during the heating period, the heat from the air channel of the sunspace, Trombe wall, and DSF is sent to the central air conditioning room, from where it is then distributed and stored throughout the building by way of air circulation. Further, during the cooling period, the cooling load can be reduced by opening the windows on the outside of the sunspace and using the roof and wing walls to provide shade from the sun. The experimental work introduced here mainly focuses on the analysis of the performance of the sunspace, when the air is sent to the central air conditioning room from the air channel of the sunspace. The sunspace is located on the south side of the house with a central air conditioning and air circulation system. The house in Miyazaki, Japan. We ran numerical simulations using THERB for HAM software to investigate effective methods of using the heat from inside the air channel (sunspace, DSF and Trombe wall), as well as possible structural improvements. We also conducted the energy performance comparison between a sunspace, double skin facade and Trombe wall.

In the chapter 1, background, previous research, objectives, purposes, and configuration of the thesis are described.

In the chapter 2, an overview of the demonstration house and simulation conditions.

In the chapter 3, we conducted an actual survey to understand the situation of heat utilization of the sunspace and used numerical simulations to examine the effective method of heat utilization of the sunspace. When air conditioning is used all day, the heating load can be reduced by combining heat collected inside the sunspace with duct-style central air conditioning. However, we confirmed that, under normal use, the temperature inside the sunspace remains high even if the air is circulated, resulting in overheating. Raising the sunspace’s ability to store heat leads to a gentler drop in its nighttime temperature, enabling an extension of the period during which airflow is circulated in the air conditioning room. When air conditioning is not used, there are times when the rooms bordering the sunspace can be heated to a comfortable temperature by opening the windows to the sunspace during the daytime; it can, therefore, be concluded that it is preferable to position the main living areas next to the sunspace. When intermittent air conditioning is used, on sunny days, the living room/dining room/kitchen area can be kept at a comfortable temperature even after the air conditioning has been stopped by only using the airflow from inside the sunspace.

In the chapter 4, we conducted an actual survey of the thermal environment for demonstration houses in Miyazaki city and analyzed the thermal environment of each room. In winter, when the air conditioning temperature is set to 22 °C, the temperature of each room can be maintained at 20 °C by the central air conditioning even in the lowest outdoor air temperature. When the solar radiation is sufficient, the temperature inside the sunspace is 40 °C or higher, so we can confirm that sunspace is effective in collecting the heat. On sunny days, when the air in the sunspace is sent to the air conditioning room, the temperature in the sunspace drops slightly and the temperature is kept high. Therefore, it is necessary to consider ways to further use the heat inside the sunspace, such as adding additional thermal storage in the sunspace. In the intermediate period, the air conditioner was turned off, and the temperature of each room was maintained by sending the heat from the sunspace to the air conditioning room. In addition, in May, although the nighttime outdoor air temperature is lower than 20 °C, the air conditioning is turned off, and the air in the sunspace is not sent to the air conditioning room, but each room is at a comfortable temperature (22 °C ~ 28 °C). That's because the high insulation performance of the house can prevent the temperature from falling. In summer, each room is kept at a comfortable temperature (25 °C ~ 28 °C) by opening the outside window of the sunspace and turning on the air conditioning. Due to the high thermal insulation of the house, outdoor air has little effect on the indoor cooler air. During the day and night of the whole year, the temperature of each room will change with the change of outdoor air temperature and solar radiation and be kept at a comfortable temperature. In addition, due to the influence of solar radiation, there is a certain temperature difference between the north and south and the east and west rooms (± 3 °C). It can be concluded that the central air conditioning and air circulation system can adjust the comfort quickly and efficiently.

In the chapter 5, the main purposes of this chapter are to identify heat collection effects and heating load reduction effects of a sunspace structure based on numerical simulation by examining efficient heat utilization methods within a sunspace and floor plans in winter. For the case of the all-day central HVAC system, it was confirmed that the larger capacity of the sunspace structure, and not sending air from the sunspace space to the adjacent room, demonstrated a better heating load reduction effect. Compared to the house without the sunspace (Model Io), the house with the sunspace on the second floor (Model I) could save about 15.6% of energy in Case 1 (air flow from the sunspace to the central HVAC machine room), about 16.3% in Case 2 (air flow from the sunspace to the central HVAC machine room and adjacent room), and about 8.6% in Case 3 (air flow from the sunspace to the adjacent room). The difference between Case 1 and Case 2 was small. Compared to the Model Io, The house with the sunspace on the first and second floors (Model II) could save about 29.9% of energy in Case 1, about 33.9% in Case 2, and about 18.5% in Case 3. Sending heat from the sunspace space to the adjacent room led to a temperature increase in the adjacent room. However, if the construction plan is to have a sunspace structure only on the second floor, the house should be carefully designed, for example, by placing a living room on the second floor. The annual heating load increased with an additional air conditioner. During the high temperature of the sunspace, the heating load can be reduced by using the adjacent room. It is advisable to design the room where the resident lives for a long time in the daytime beside the sunspace.

In the chapter 6, numerical studies on the energy performance of the sunspace, DSF (double skin facade) and Trombe wall were carried out. In all cases, the larger capacity of the sunspace, double skin facade and Trombe wall structure had a greater heating load reduction effect. In all Models with intermittent air conditioning or intermittent individual room air conditioning, the heating load increased when the air conditioning system is used again after the air conditioning system is stopped. It can be concluded that when the air conditioning system is turned off, the temperature of the air conditioning room decreases, and when the air conditioning system is turned on again, a large amount of energy is required to reach the air conditioning setting temperature. In the case of all-day air conditioning, the Trombe wall has the best energy performance, followed by double skin facade. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 12.18% of energy, about 29.57%, about 13.44%, about 32.88%, about 14.06% and about 39.69%, respectively. In the case of intermittent air conditioning, the Trombe wall (first- and second-floor) has the best energy performance, followed by double skin facade (first- and second-floor). The double skin facade (first-floor) has the best energy performance, followed by Trombe wall (first-floor). Compared to the Model Io, Models I, II, III, IV, V and VI could save about 10.27% of energy, about 13.03%, about 11.53%, about 17.56%, about 11.43% and about 17.64%, respectively. In the case of intermittent individual room air conditioning (housewife), the sunspace has the best energy performance, followed by Trombe wall. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 19.40% of energy, about 35.27%, about 15.25%, about 30.95%, about 18.23% and about 31.03%, respectively. In the case of intermittent individual room air conditioning (worker), the Trombe wall has the best energy performance, followed by double skin facade. Compared to the Model Io, Models I, II, III, IV, V and VI could save about 13.41% of energy, about 24.38%, about 14.35%, about 24.74%, about 16.67% and about 28.77%, respectively.

In the chapter 7, we clarified the thermal environment of each room during heat utilization of the sunspace, double skin facade and Trombe wall and examined whether it is possible to maintain thermal environment suitable for daily behavior. In the case of Models I, III and V with all-day air conditioning, even if the heat is sent from the air cavity (sunspace, DSF and Trombe wall) to the central air conditioning room, the air cavity (sunspace, DSF and Trombe wall) temperature does not decrease and maintains high temperature. In the case of Models I, II, III, IV, V and VI with intermittent air conditioning, even if the central air conditioning is turned off, the temperature in each room is above 20°C for most of the time, and it can be seen that the each room temperature increases with the necessary ventilation. Therefore, by increasing the ventilation of the bedroom and washroom that are not affected by solar radiation, the amount of heat in the central air conditioning room can be effectively used to increase the proportion of nighttime temperature that exceed 20°C. In the case of Models I, II, III, IV, V and VI with intermittent individual room air conditioning (worker), the temperature of the central air conditioning room temporarily decreased after the central air conditioning was turned off, but the central air conditioning room temperature rose due to the air circulation between the air cavity (sunspace, DSF and Trombe wall) and the central air conditioning room. Therefore, it is possible to reduce the ratio of the temperature below 20°C during the nighttime by sending the heat from the air cavity (sunspace, DSF and Trombe wall) to rooms that are not used during the daytime.

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