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A Case Study of a Nursing Home in Nagano, Japan: Field Survey on Thermal Comfort and Building Energy Simulation for Future Climate Change

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Abstract: With an increase in the aging population in many countries worldwide, much attention is being paid to the study of thermal comfort for the elderly. Because the elderly spend most of their time indoors, the demand for air conditioning is expected to increase, and it is important to study the thermal comfort of the elderly and appropriate operation plans for air conditioning. In this study, we conducted a field survey of thermal comfort and building energy simulation for an air-conditioned nursing home in Nagano, Japan. The field survey was conducted between June 2020 and June 2021. Over 80% of the subjects were satisfied with the indoor thermal environment. The thermal neutral temperature of the elderly was 25.9 °C in summer and 23.8 °C in winter. Future weather data was used to predict the future heating and cooling loads of the nursing home. The results showed that the total heat load may not change significantly, as the decrease in heating load compensates for the increase in cooling load. This study will serve as a useful reference for a wide range of stakeholders, including managers and designers of nursing homes.

Keywords: elderly people; nursing home; thermal comfort; climate change; building energy simulation

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1. Introduction

Climate change is one of the biggest challenges of our times [1]. The global average temperature in 2011–2020 was 0.99 °C higher than in 1850–1900. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global average temperature was projected to increase by 1.5 °C over the 1850–1900 temperature range within the next 20 years, and global warming will increase the frequency and intensity of extreme weather events, including heat waves, heavy rains, and droughts [2]. An increase in temperature owing to climate change increases thermal stress in the human body and increases the risk of various diseases such as heat stroke risk and respiratory diseases [3]. In particular, the elderly, whose ability to regulate body temperature is reduced, are significantly influenced by heat waves [4]. At least 15,000 people died in the 2003 heat wave in France, and approximately 79% of all deaths were people aged 65 and above [5]. In Japan, the number of people transported to emergency rooms owing to heat stroke exceeded 95,000 in 2018, the highest number ever since the survey began in 2008 [6]. Over 1500 people died from heat stroke that year, and approximately 82% of all deaths were in people aged 65 and above [7]. In addition to the promotion of energy conservation to control climate change, the health and thermal comfort of the elderly should be considered.

Population aging and climate change are key issues of the 21st century [8,9]. Many countries are experiencing population aging worldwide, and much attention has been paid to studying the thermal sensation of the elderly and their demands on the thermal environment of buildings [10]. Japan is a country with a high life expectancy, with 28.7% of its total population aged 65 and above in 2020, and this age group is expected to increase to 35.3% by 2040 [11]. As reported in previous studies, the elderly spend more time indoors than younger people [12,13], and an increase in the elderly population, who spend more time indoors, is expected to increase the demand for air conditioning. Investigating the effects of the thermal environment on the elderly is not only beneficial for providing a comfortable and healthy environment for the elderly but also to consider appropriate operational plans to control the heating and cooling loads in elderly facilities [10].

Laboratory experiments investigating the effects of aging on thermal comfort focused on thermal neutrality and thermal sensitivity. Fanger [14] conducted a comparative study of 128 elderly people and 128 university students and found that there was no difference in neutral temperature between the two groups. The author argued that the same neutral temperature for the elderly and the young stems from the fact that metabolic rate and evaporative heat loss decrease with age. Natsume et al. [15] compared the preferred temperatures in both groups of elderly and young adults, each consisting of six male subjects. The results showed that the fluctuations of the preferred temperature were significantly observed in the elderly than in the young, indicating a decrease in thermal sensitivity with aging. Tsuzuki et al. [16] found that the elderly had lower warm sensitivity in the cold season and lower cold sensitivity in the hot season compared with university students. Collins et al. [17] conducted a comparative study of preferred temperature in 17 elderly and 13 young adults while wearing clothing providing 0.8 clo. The results showed that the preferred temperatures of the elderly and the young were the same, but the elderly were less able to accurately manipulate the ambient temperature and reported greater temperature variability than the young. Sassa et al. [18] investigated the temperature preference of 94 healthy elderly people in Japan while wearing clothing providing 0.4 clo and compared the results with those of previous studies. The results suggested that the elderly controlled their preferred temperature less frequently than the younger generation owing to a decrease in thermal perception and that they did not adjust their temperature. The results were compared with those of a previous survey of young Japanese. Xiong et al. [19] investigated the perceptual and physiological responses of 16 healthy elderly people in Shanghai during the summer and compared the results with those of a survey of university students in Shanghai [20]. The results showed that there was no difference in the neutral temperature between the two groups, whereas the elderly were not as sensitive as the university students on temperature change. These studies support the finding that many healthy elderly people prefer the same temperature as younger adults in a static environment. In addition, it has been shown that the elderly may not be able to manipulate the temperature accurately in a study in which the preferred temperature was determined by the self-selection of the indoor temperature and that thermal sensitivity decreases with age.

Several field studies have been conducted to investigate the living environment of elderly people. Comparative analysis of residents (elderly) and non-residents of elderly care facilities reported differences in thermal neutrality, thermal sensitivity, and occupant behavior to heat and cold in the two groups. Forcada et al. [21] conducted a summer study of nursing home residents and non-residents (caregivers and therapists) in Spain. They showed that the neutral temperature of the residents (25.3 °C) was 1.4 °C higher than that of the non-residents (23.9 °C). In addition, Forcada et al. [22] conducted a study in winter, which showed that residents had lower thermal sensitivity and were more tolerant of indoor temperature changes compared to non-residents. They reported that elderly people adjusted their clothing to changes in indoor temperature and activity levels, whereas non-residents did not adjust their clothing to adapt to unsatisfactory temperature conditions and activities. Tartarini et al. [23] conducted a study of nursing home residents and non-residents (residents' families and staff) in Australia. A comparative study was conducted on the subjects. In the thermal sensation vote (TSV) survey, residents were more tolerant of the thermal environment than non-residents, with 77% reporting it as neutral (TSV = 0). Only

39% of non-residents reported neutral (TSV = 0). In a separate study by Tartarini et al. [24], residents reported a preference for warmer indoor temperatures than non-residents. These field surveys reported that residents and staffs have different thermal comfort requirements in nursing homes owing to differences in the type of activities, clothing insulation worn, time spent indoors, and health status. In general, staff who manage the temperature of indoor spaces should understand the thermal sensation of the residents. However, owing to the difference in thermal requirements between the two groups, there is a concern that staff may unintentionally select temperature settings that residents do not want. To analyze the staff's perception of the residents' thermal sensations, this study conducted a questionnaire survey in which the staff expected and answered the residents' thermal sensations.

The most common thermal comfort model as a guide for air-conditioned indoor space design is the predicted mean vote (PMV) [25]. However, comparative analyses of TSV and PMV in senior citizens from several field studies suggested the limitations of PMV [26,27]. Jin et al. [28] found that in a study of 11 senior citizens aged 83–94 in a Scottish care home during winter, the neutral temperature predicted by PMV was reported to be 2.7 °C lower than the neutral temperature estimated from TSV. Jiao et al. [8] also obtained similar results in winter surveys in a survey of elderly people's homes in Shanghai, China, and Wong et al. [29], in a survey of nursing homes in Hong Kong, showed that residents were thermally neutral when PMV had a negative value. Conversely, the summer study of Jiao et al. [8] did not identify any significant difference between TSV and PMV neutral temperatures. In addition, Yang et al. [30] reported seasonal differences in the thermal neutrality agreement between TSV and PMV by regression analysis in their annual survey of elderly care facilities in Korea. To date, there are limited annual surveys of thermal comfort in elderly care facilities [10], and further field surveys are required to conduct transverse analyses.

In addition to investigating thermal comfort in the elderly, occupant behavior to reduce heat stress has also been investigated. Hwang et al. [31] investigated occupant behaviors in 87 elderly people in their homes in Taiwan during the summer and winter. Although air conditioning was available in most houses of these elders, the most common occupant behaviors observed during summer were, in order, opening windows (38%), adjusting clothing (28%), and using electrical fans (25%). The most common occupant behavior observed during winter was adjusting clothing (64%), followed by using mechanical heating (17%). Giamalaki et al. [32] investigated occupant behaviors during the cooling and heating season in 30 elderly people in their homes in Crete, Greece. They reported that energy costs were the most influential factor in their strategies in rooms with dissatisfactory thermal environments. White-Newsome et al. [33] investigated occupant behaviors among elderly people to high indoor and outdoor temperatures in 29 homes in Detroit, MI, USA. As behaviors to adapt to high indoor temperatures, most respondents reported opening windows or doors, using electrical fans, leaving the house, and taking a shower. There was a statistically significant increase in changing clothes when the temperature ranged from 24.4 to 26.6 °C. Occupant behaviors to hot temperatures decreased when the indoor temperatures were above 29.4 °C. These findings reported that elderly people use a variety of methods to reduce their thermal dissatisfaction with indoor temperature; however, they may not perform occupant behaviors and be exposed to heat risks in high-temperature environments. These studies were also conducted with healthy elderly people in homes. Compared to healthy elderly people in homes, elderly people residing in elderly care facilities may have limited occupant behaviors to compensate for thermal discomfort owing to dementia or physical limitations [23].

Heating, ventilation, and air-conditioning (HVAC) systems are normally operated with the objectives of optimizing resident comfort, workplace productivity, and energy conservation [34]. The building sector accounts for approximately 40% of the world's final energy consumption and approximately 33% of the CO_2 emissions [35]. The building sector accounts for approximately 40% of the world's final energy consumption and approximately 33% of the CO_2 emissions [35]. The increase in energy consumption in recent years results from the widespread use of HVAC equipment to meet the thermal needs in the built environment [22]. In developed countries, HVAC is the largest energy end-use, accounting for approximately half of the energy consumption in buildings, especially non-residential buildings [35]. In current coronavirus (COVID-19) times, ventilation plays an important role in the mitigation of viral loads in a confined space [36]. The post-COVID-19 occupancy-based HVAC system control requires the consideration of sustainable strategies to create a synergy between occupant's health and building energy efficiency [36].

An increase in the global average temperature owing to climate change is expected to reduce heating loads and increase cooling loads, in addition to the risks associated with adverse effects on human health and reduced thermal comfort [37,38]. Building simulation studies often focus on offices and residents, with limited research on elderly care facilities [39,40]. Studies on building simulations for elderly care facilities include the following. Hirvonen et al. [41] developed six different building models in Finland, including an elderly care facility, and analyzed the potential for CO_2 emissions reductions in 2050 using building retrofit scenarios for each building model. For the retrofit of the elderly facility, the following measures were considered: installation of mechanical air supply and exhaust ventilation systems with heat recovery, improvement of the thermal insulation of exterior walls and roof, installation of energy-efficient windows, automatic lighting control, and the use of solar thermal and solar electric systems. CO_2 emissions in the retrofit scenario were shown to have the potential to be reduced by 50 to 75% by 2050. Because the study focuses on heating demand in Finland, cooling loads were not calculated. Sun et al. [42] replicated a real nursing home in Florida, USA, and examined the impact of passive and active energy efficiency measures on occupant resilience during a weather-related disaster. They reported that passive measures such as the placement of aluminum foil on the roof and windows, installation of a cool roof, modification of windows, and the addition of more wall insulation had some effect on the reduction in the indoor heat index; however, it could not guarantee safe conditions for occupants. They also concluded that air conditioning was necessary to maintain a safe indoor environment for the occupants and that active measures such as energy storage devices with half the capacity of the cooling system and solar power generation were necessary. These studies only evaluated the heating or cooling loads and did not include the total heat load in their analysis. In addition, building energy simulations for elderly care facilities investigating the impact of future climate change have not been conducted in Japan. Furthermore, to date, there is no consensus on the impact of thermal insulation in climate change scenarios [38], and further research is required. These are the gaps that need to be addressed and are the focus of the building analysis in this study.

In this study, a questionnaire-based survey of thermal comfort and measurements of the indoor thermal environment was conducted in an air-conditioned elderly care facility in Nagano, Japan. Thermal comfort was evaluated using the thermal sensation of the elderly and the staff, as well as the staff's expected thermal sensation of the residents. In addition, future forecasts of annual heating and cooling loads in the subject building were analyzed using future weather data from the present to 2050, and the impact of window insulation performance on heating and cooling loads was examined.

2. Methods

2.1. Field Survey

In this study, a survey of an indoor thermal environment and a subjective vote survey was conducted in an elderly care facility. The target area of this study was Nagano City, Nagano Prefecture, Japan (36.67° N–138.20° E). Nagano City is located in the central part of Japan. According to the Köppen climate classification, Nagano City is classified as a humid subtropical climate (Cfa) [43]. Figure 1 shows the monthly mean outdoor air temperature (t_{out}) and relative humidity (RH) for the study period (June 2020–June 2021). January had the lowest outdoor air temperature, with a mean daily minimum outdoor air temperature of -3.2 °C. August had the highest outdoor air temperature, with a mean daily maximum outdoor air temperature of 33.5 °C. The outdoor environmental data were obtained from the Japan Meteorological Agency [44].

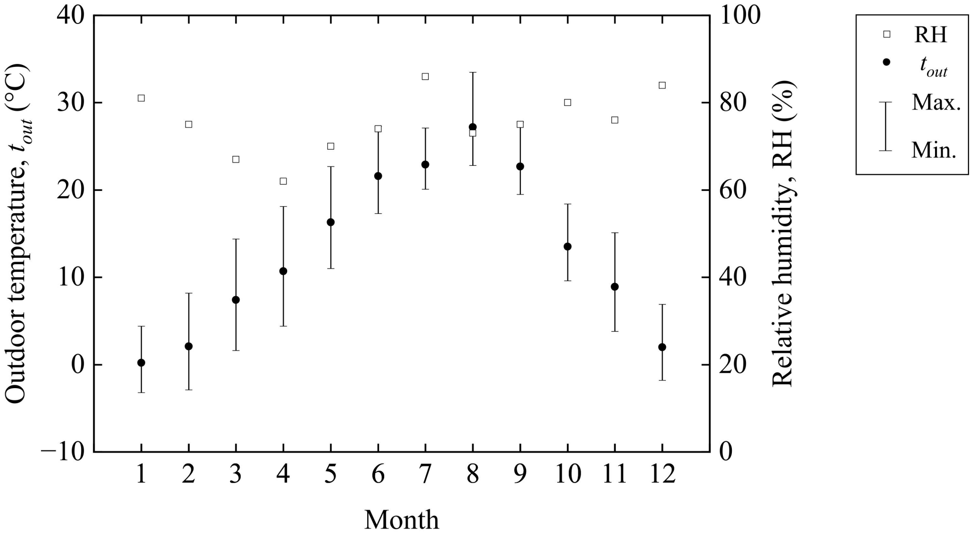


Figure 1. Monthly mean outdoor air temperature and relative humidity during the survey period.

This study was conducted in a nursing home in Nagano City. The surveyed facility accommodates elderly people who have been certified as eligible for nursing care. This survey was conducted throughout the year. This study was conducted from 8 June 2020, to 7 June 2021. In this study, May to October is defined as the summer period and November to April as the winter period. The subject building is a two-story steel structure. The total floor area is 1352.50 m^2 (585.16 m^2 for the first floor and 767.34 m^2 for the second floor), and the height of the ceiling is 3.3 m for each floor. The residents mainly live in the common space on the first floor during the daytime and in the rooms on the second floor at night. The measurement point of this study is the common space on the first floor, where the residents spend most of their time during the day. The room to be surveyed is used for multiple purposes, such as checking the residents' vitals, eating, and socializing with other residents. In addition, because the room under investigation was controlled by air conditioning throughout the year during the residents' stay, the type of building was air-conditioned mode (AC mode). No fans or warming devices were used in this room; however, one humidifier was used when the heating system was in use. The subjects of this study were 66 residents (aged 65 and above) and one staff member (a woman in her 50s). The average age of all residents who participated in the study was 83.7 years (Table 1).

Table 1. Age distribution of residents.

Season	Sample Size	Gender		Age Group							Age
		Male	Female	65–69	70–74	75–79	80–84	85–89	90–94	95+	Mean
Summer	4686	24	38	2	4	14	15	12	13	2	83.4
Winter	5331	19	28	2	4	7	15	9	8	2	83.4
All season	10,017	27	39	2	4	14	17	12	14	3	83.7

2.1.1. Survey of the Indoor Thermal Environment

The measurement items of the indoor thermal environment were air temperature (t_a), RH, globe temperature (t_g), and air velocity (V). Figure 2 shows the survey building and Figure 3 shows the measurement points. The measurement points were set according to ISO 7726 [45]. The air temperature was measured at 0.1 m and 1.1 m above the floor. RH, globe temperature and wind speed were measured at a height of 1.1 m above the floor.

The measurement intervals for air temperature, RH, and globe temperature were 10 min. Wind speed was measured continuously for 5 min. Indoor wind speed was measured once during each season, and the mean value of the measured data was used for analysis. Table 2 and Figure 4 show the specifications of the measuring instruments used for the thermal environment survey.

Figure 2. Survey objects: (**a**) survey building; (**b**) survey room.

2.1.2. Subjective Vote Survey

In this study, we investigated the subjective votes of residents and staff. The subjective survey of the residents was based on the interviews of the staff members. For the subjective survey of the staff, forms were distributed and requested to be filled out. This study respected the basic principles of the Declaration of Helsinki and was approved by the Ethics Committee of Shinshu University. The survey was conducted after obtaining consent from the subjects. The subjective vote survey included attributes of the subjects, thermal sensation, metabolic rate, and clothing insulation. The attributes included age, gender, and care level (residents only) required. There are two types of TSV: one is a question in which subjects answer their own thermal sensation, and the other is a question in which the staff predicts the thermal sensation of residents (imaginal thermal sensation vote, TSV_i). The subjective survey of residents was conducted once a day with the subject at rest during the daily vital examination after waking up. The subjective survey of the staff was conducted twice a week, up to thrice a day (voting interval is more than one hour). The survey on the clothing insulation by staff expected to wear uniforms was conducted once a month. The metabolic rate of the staff was surveyed during the period 1 February 2021 to 7 June 2021. The staff were instructed to respond to the questionnaire at any time of the day, but to avoid responding immediately after a meal to reduce the effects of non-stationarity. The questionnaires were filled in by staff members. Figure 5 shows the questionnaire used for the subjective survey.

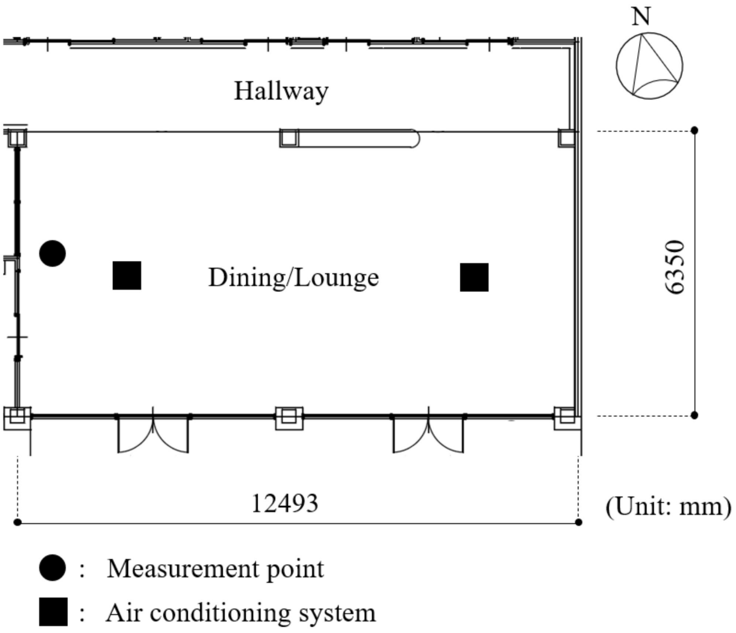


Figure 3. Floor plan and measurement points.

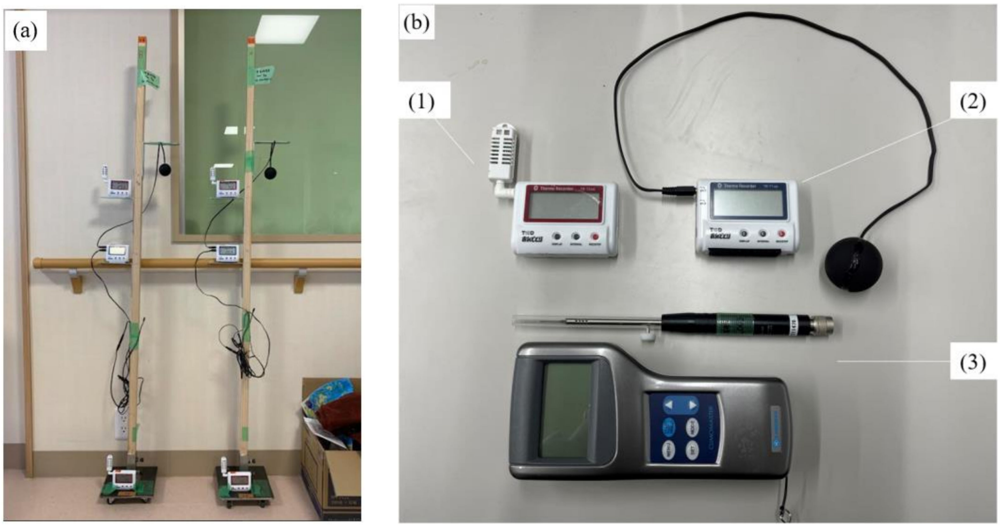
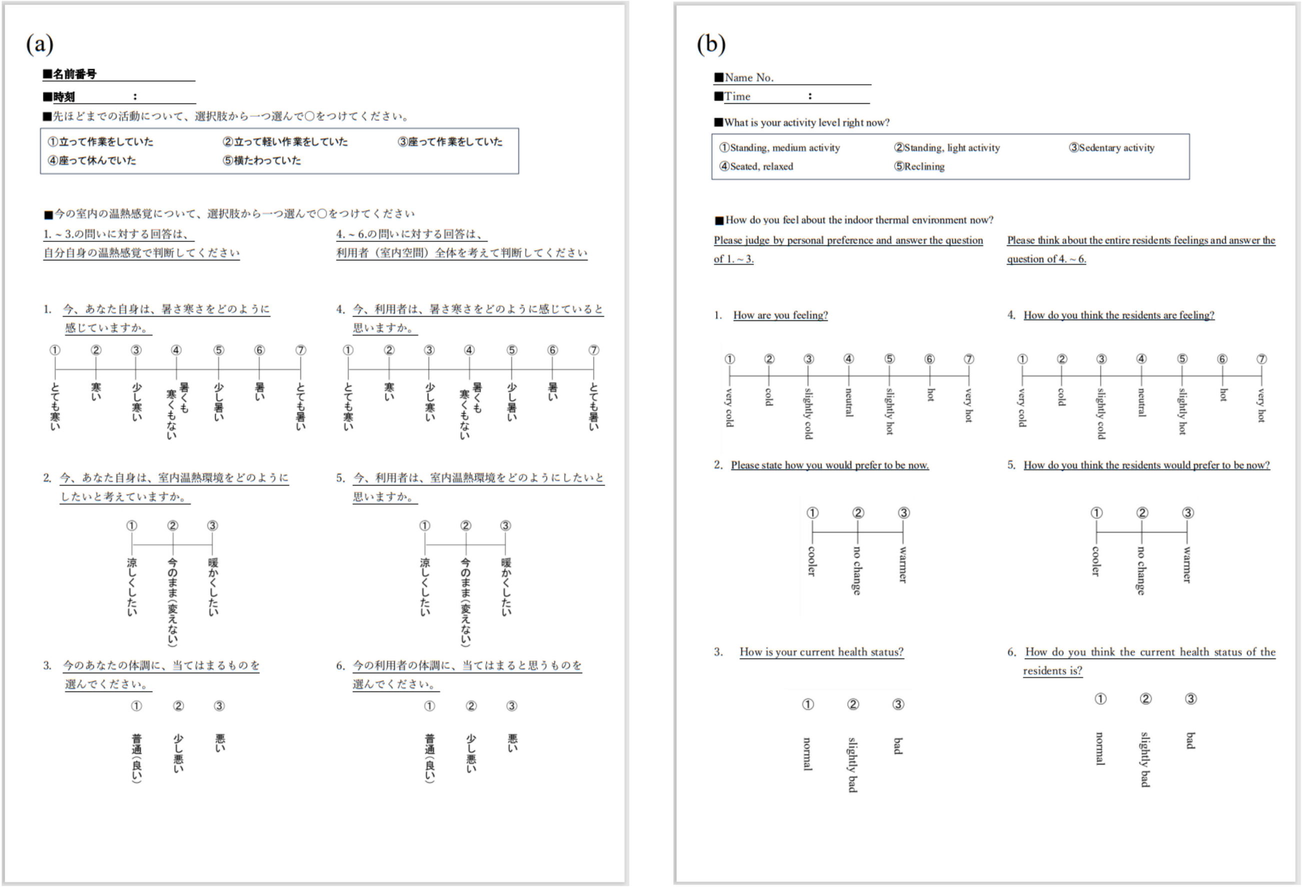


Figure 4. Details of the environmental measurement: (**a**) Installation of measurement instruments. (**b**) Measuring instruments; (**1**) Thermo recorder TR-72wb; (**2**) Thermo recorder TR-71wb; (**3**) Climomaster 6501-B0 (body) and Climomaster 6541-21 (probe).

Table 2. Details of the instruments used for environmental measurement.

Parmenter	Instrument	Resolution	Accuracy	Manufacture
t_a RH	Thermo recorder TR-72wb	0.1 °C 1%	±0.5 °C ±5%	T&D corporation
t_g	Thermo recorder TR-71wb	0.1 °C	±0.3 °C	
V	Body: Climomaster 6501-B0 Probe: Climomaster 6541-21	0.01 m/s	±0.02 m/s	Kanomax corporation

t_a: air temperature, RH: relative humidity, t_g: globe temperature, V: air velocity.



(a)

■名前番号

■時刻　　　：

■先ほどまでの活動について、選択肢から一つ選んで○をつけてください。

①立って作業をしていた　②立って軽い作業をしていた　③座って作業をしていた
④座って休んでいた　⑤横たわっていた

■今の室内の温熱感覚について、選択肢から一つ選んで○をつけてください

1.～3.の問いに対する回答は、自分自身の温熱感覚で判断してください

4.～6.の問いに対する回答は、利用者（室内空間）全体を考えて判断してください

1. 今、あなた自身は、暑さ寒さをどのように感じていますか。
① とても寒い ② 寒い ③ 少し寒い ④ 暑くも寒くもない ⑤ 少し暑い ⑥ 暑い ⑦ とても暑い

2. 今、あなた自身は、室内温熱環境をどのようにしたいと考えていますか。
① 涼しくしたい ② 今のまま（変えない） ③ 暖かくしたい

3. 今のあなたの体調に、当てはまるものを選んでください。
① 普通（良い） ② 少し悪い ③ 悪い

4. 今、利用者は、暑さ寒さをどのように感じていると思いますか。
① とても寒い ② 寒い ③ 少し寒い ④ 暑くも寒くもない ⑤ 少し暑い ⑥ 暑い ⑦ とても暑い

5. 今、利用者は、室内温熱環境をどのようにしたいと思いますか。
① 涼しくしたい ② 今のまま（変えない） ③ 暖かくしたい

6. 今の利用者の体調に、当てはまると思うものを選んでください。
① 普通（良い） ② 少し悪い ③ 悪い

(b)

■Name No.

■Time　　　:

■What is your activity level right now?

①Standing, medium activity　②Standing, light activity　③Sedentary activity
④Seated, relaxed　⑤Reclining

■How do you feel about the indoor thermal environment now?

Please judge by personal preference and answer the question of 1. ~ 3.

Please think about the entire residents feelings and answer the question of 4. ~ 6.

1. How are you feeling?
① very cold ② cold ③ slightly cold ④ neutral ⑤ slightly hot ⑥ hot ⑦ very hot

2. Please state how you would prefer to be now.
① cooler ② no change ③ warmer

3. How is your current health status?
① normal ② slightly bad ③ bad

4. How do you think the residents are feeling?
① very cold ② cold ③ slightly cold ④ neutral ⑤ slightly hot ⑥ hot ⑦ very hot

5. How do you think the residents would prefer to be now?
① cooler ② no change ③ warmer

6. How do you think the current health status of the residents is?
① normal ② slightly bad ③ bad

Figure 5. Subjective questionnaire: (**a**) Questionnaire used in this study. (**b**) Questionnaire translated into English.

The scales and options on TSV and TSV_i were prepared with reference to ISO 10551 [46] and ASHRAE Standard 55 [47]. Because subjects in this study were Japanese, it was necessary to translate to Japanese. Japanese translations were obtained from AIJES-H0004 (Architectural Institute of Japan Environmental Standard) [48]. The metabolic rate was based on the ASHRAE Standard 55 [47], and residents were assumed to be in a chair-seated resting state (1.0 met). The metabolic rate of the staff, who were assumed to be engaged in a variety of activities, could choose from five levels. The clothing insulation was selected from seven levels of clothing assumed to be worn by the subjects. The total estimated clothing insulation was calculated by integrating the clo values with reference to the ASHRAE Standard 55 [47]. The clo value of down jackets was 0.55, which are not listed in ASHRAE, with reference to ISO 7730 [49]. The clothing insulation worn by the resident was determined by having the staff fill in the most applicable option as the resident's clothing. The items and scales of the subjective votes are shown in Table 3; Figure 6 shows the choices of the clothing insulation, and Table 4 shows the 12 items of clothing used in the combination of the clothing insulation and the corresponding clo values.

Table 3. Summary of questionnaire items, scales, and numerical coding used in the analysis.

Question	Scale
Attribute	age, gender, care level
Metabolic rates	1: standing work, 2: light standing work, 3: sitting work 4: seated quiet, 5: reclining
Thermal sensation	−3: very cold, −2: cold, −1: slightly cold, 0: neutral +1: slightly hot, +2: hot, +3: very hot

Table 4. Clothing items used in this survey.

Garment Description	I_{cl} (clo)
Men's briefs or bra + panties	0.04
Walking shorts	0.08
Straight trousers (thin)	0.15
Straight trousers (thick)	0.24
Short-sleeve dress shirt	0.19
Long-sleeve dress shirt	0.25
Long-sleeve sweatshirt	0.34
Jumper	0.27
Down jacket	0.55
Ankle-length athletic socks	0.02
Calf-length socks	0.03
Slippers (quilted, pile lined)	0.03

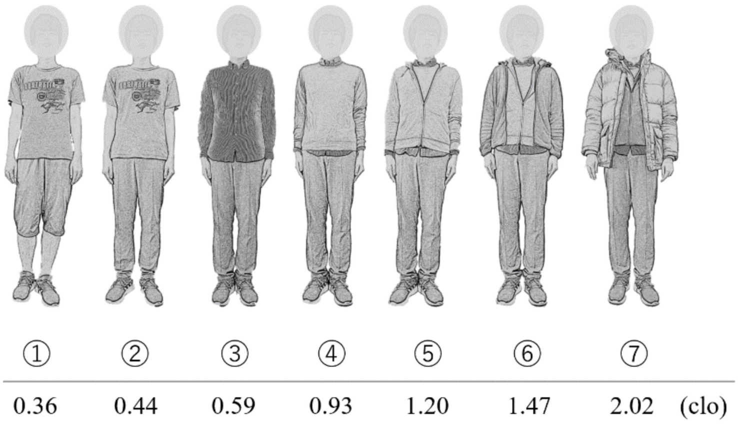


Figure 6. Scale of clothing insulation.

2.1.3. Characteristics of Residents

Twenty-seven male and thirty-nine female residents participated in the survey. Table 5 shows the distribution of the level of care required by the residents who participated in this survey. The care level required is indicated by five levels, from 1 to 5, and the number is proportional to the time required for care [50]. According to a study that examined the characteristics of people who are likely to be certified as requiring nursing care, a wide range of factors were reported, including frailty [51], decline in cognitive and mental functions [52], decline in physical functions [53], lack of social activities [54], and decline in renal function [55]. The top causes of the need for nursing care were dementia (18%), stroke (16.6%), and old age-related weakness (13.3%) [50].

Table 5. Distribution of residents' care level.

Gender	Number of People	Care Level				
		1	2	3	4	5
Male	27	5	7	6	6	3
Female	39	5	6	6	15	7

2.1.4. Thermal Indices

The thermal indices calculated in this study were PMV, new effective temperature (ET*), and operative temperature (t_o). PMV and ET* were calculated by inputting the values of air temperature, mean radiant temperature, humidity ratio, atmospheric pressure, wind speed, clothing insulation, and metabolic rate into the ASHRAE Thermal Comfort Tool version 1. PMV and ET* at the time of staff declaration were calculated using the mean metabolic rate of staff reported in this study (1.4 met). The atmospheric pressure data were obtained from Japan the Meteorological Agency [44]. The operative temperature was calculated according to the ASHRAE Standard 55 [47] from the following equation.

$$t_o = At_a + (1 - A)\, t_r \tag{1}$$

t_o: operative temperature (°C)
t_a: air temperature (°C),
t_r: mean radiant temperature (°C),
A: coefficient (0.5) (-).

The mean radiant temperature was calculated from the following equation according to ISO 7726 [45].

$$t_r = \left[\left(t_g + 273.15\right)^4 + \frac{1.06 \times 10^8\ V^{0.6}}{\varepsilon\ D^{0.4}} \left(t_g - t_a\right) \right]^{0.25} - 273.15 \tag{2}$$

t_r: mean radiant temperature (°C),
t_g: globe temperature (°C),
t_a: air temperature (°C),
V: air velocity (m/s),
ε: emissivity of the globe sphere surface (0.94) (-),
D: diameter of the globe sphere (0.04) (m).

2.1.5. Comfort Zone

ASHRAE Standard 55 [47] describes a simplified analytical comfort zone method to determine the thermal comfort range. This thermal environment criterion can be used to create an acceptable range equivalent to 80% with a mean air wind speed of less than 0.20 m/s, an occupant's metabolic rate of 1.0–2.0 met, and clothing insulation of 0–1.5 clo. The calculation conditions of the comfort zone were set at $-0.5 < \text{PMV} < +0.5$ to account for local discomfort in real environments [56]. The boundaries of the acceptability limits were calculated using the mean values of wind speed, clothing insulation, and metabolic rate for each season measured in this study. The comfort zone of the staff was calculated using the mean value of the metabolic rate of the staff reported in this study (1.4 met). Boundaries of acceptability limits were calculated using the ASHRAE Thermal Comfort Tool version 1.

2.1.6. Adaptive Thermal Comfort Model

The indoor thermal environment was evaluated by comparing the adaptive thermal comfort model (adaptive model) according to ISO 17772-1 [57] with the survey data of this study. The adaptive model uses the running mean outdoor temperature as the explanatory variable and the indoor operative temperature as the objective variable; the acceptable temperature range of the ISO 17772-1 adaptive model is 7 °C at 80% (Category II) and 5 °C at 90% (Category I). Each category relates to the level of expectations the occupants might have. Category II is a level to meet medium expectations. Category I is a level to meet higher expectations, recommended when considering the requirements of special occupancy groups such as children, the elderly, and persons with disabilities. The upper and lower limits of the adaptive model were calculated from the following equation [57].

$$\text{Upper 80\% acceptability limit } (^\circ\text{C}) = 0.33t_{rm} + 18.8 + 3 \tag{3}$$

$$\text{Lower 80\% acceptability limit } (^\circ\text{C}) = 0.33t_{rm} + 18.8 - 4 \tag{4}$$

$$\text{Upper 90\% acceptability limit } (^\circ\text{C}) = 0.33t_{rm} + 18.8 + 2 \tag{5}$$

$$\text{Lower 90\% acceptability limit } (^\circ\text{C}) = 0.33t_{rm} + 18.8 - 3 \tag{6}$$

t_{rm}: Running mean outdoor temperature (°C).

The running mean outdoor temperature was calculated from the following equation according to ISO 17772-1 [57].

$$t_{rm} = (1 - \alpha)\left(t_{ed-1} + \alpha t_{ed-2} + \alpha^2 t_{ed-3} \ldots\right) \tag{7}$$

t_{rm}: running mean outdoor temperature (°C),
$t_{ed\text{-}i}$: daily average outdoor air temperature of the day i before (°C),
α: constant (-).

Here, α is a constant between 0 and 1. In this study, the value of α was set to 0.8 [57]. The daily mean outdoor air temperature considered the statistics of the previous seven days.

2.2. Building Energy Simulation

In this study, we modeled the nursing home in which the field survey was conducted, and we evaluated the annual heating and cooling loads in the common space. Figure 7 shows the overall methodology and workflow of this case study.

2.2.1. Weather Data

In this study, we obtained weather data for Nagano City from Meteonorm version 8.0. Meteonorm version 8.0 produces future weather data for the period from 2020 to 2100 based on the global climate models used in Coupled Model Intercomparison Project Phase 5 (CMIP5). In this study, future weather data for 2020, 2030, 2040, and 2050 were used. Typical meteorological year data were converted to EnergyPlus weather data (EPW) format for use in EnergyPlus analysis. The Fifth Assessment Report of the IPCC [58] presented projections of the average temperature increase over the next 100 years using four different scenarios called representative concentration pathways (RCP). Two scenarios, RCP 8.5 (2.6–4.8 °C increase in 2100), with the highest temperature increase, and RCP 2.6 (0.3–1.7 °C increase in 2100), with the lowest temperature increase, were used in this study for the analysis. Typical meteorological year data and two future scenarios were used to produce eight EPWs that were converted to data for 2020, 2030, 2040, and 2050.

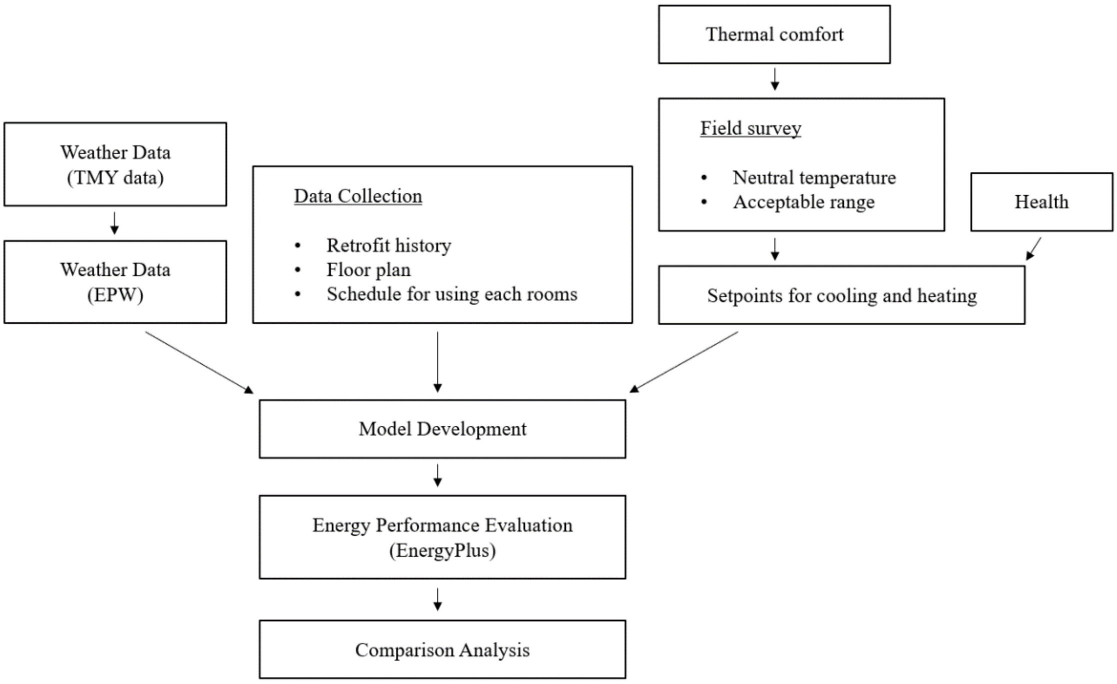


Figure 7. Study concept framework.

2.2.2. Building Data Collection and Development

The building under investigation was built in 1992 as an office building and changed its room usage from office to the current elderly care facility through renovations in 2018. The building is currently used as a mixed-use building with some existing office space remaining on the north face of the first floor. Architectural drawings used during the 2018 renovation were collected to create the building model geometry and zoning. To determine the occupancy of the elderly care facility, daily room usage schedules for each zone were collected from interviews with staff.

The building model was created using EnergyPlus 9.1.0 and Rhinoceros version 7. EnergyPlus is a building energy simulation program developed by the U.S. Department of Energy [59]. Rhinoceros is a popular graphical user interface for EnergyPlus and was used to create the building model geometry and zoning. Figure 8 shows the 3D model and floor plan created in Rhinoceros. On the first floor, dining/lounge, office room, bathroom, treatment room, kitchen, meeting room, toilets, and existing office rooms were located. The second floor contained residents' bedrooms, staff room, and toilets. The energy simulation of the building is performed on Grasshopper, a graphical programming language platform, via the Honeybee plug-in. Honeybee reads the Rhinoceros geometry, and the EPW placed on Grasshopper. EPW was placed on Grasshopper to perform the heat load simulation.

2.2.3. Building Evaluation

The ideal load air system model [60] of EnergyPlus was used to evaluate the energy performance of the building. Therefore, the equipment performance of the HVAC system was not considered in this study. The selected time step for simulation was 10 min. The output data were the hourly heating loads and cooling loads in each zone. By integrating the heating and cooling loads for 8760 h, the annual heating and cooling loads in the common space of the target building were calculated and used for analysis.

1. Internal Heat Gains, Occupancy, and HVAC: The internal heat gains and occupancy of the building were set based on the room usage of each zone and the room usage schedule of the occupants, referring to the standard room usage conditions [61] according to the Japanese energy conservation act. The internal heat gain and occupancy of the elderly facility were selected from the room usages of the hospital and hotel,

referring to the previous study by San et al. [42]. The internal heat gain and occupancy of the existing office were selected from the room usage of the office. To be consistent with the daily room usage schedule in the elderly facility, the internal heat gain and occupancy assumed in the elderly facility were adjusted based on the information collected in the interview survey. Table 6 shows the activity levels of the occupants, the heat generation by lighting, and the heat generation by equipment in each zone. In addition, the occupancy is shown in Figure 9, the lighting schedule is shown in Figure 10, and the equipment schedule is shown in Figure 11.

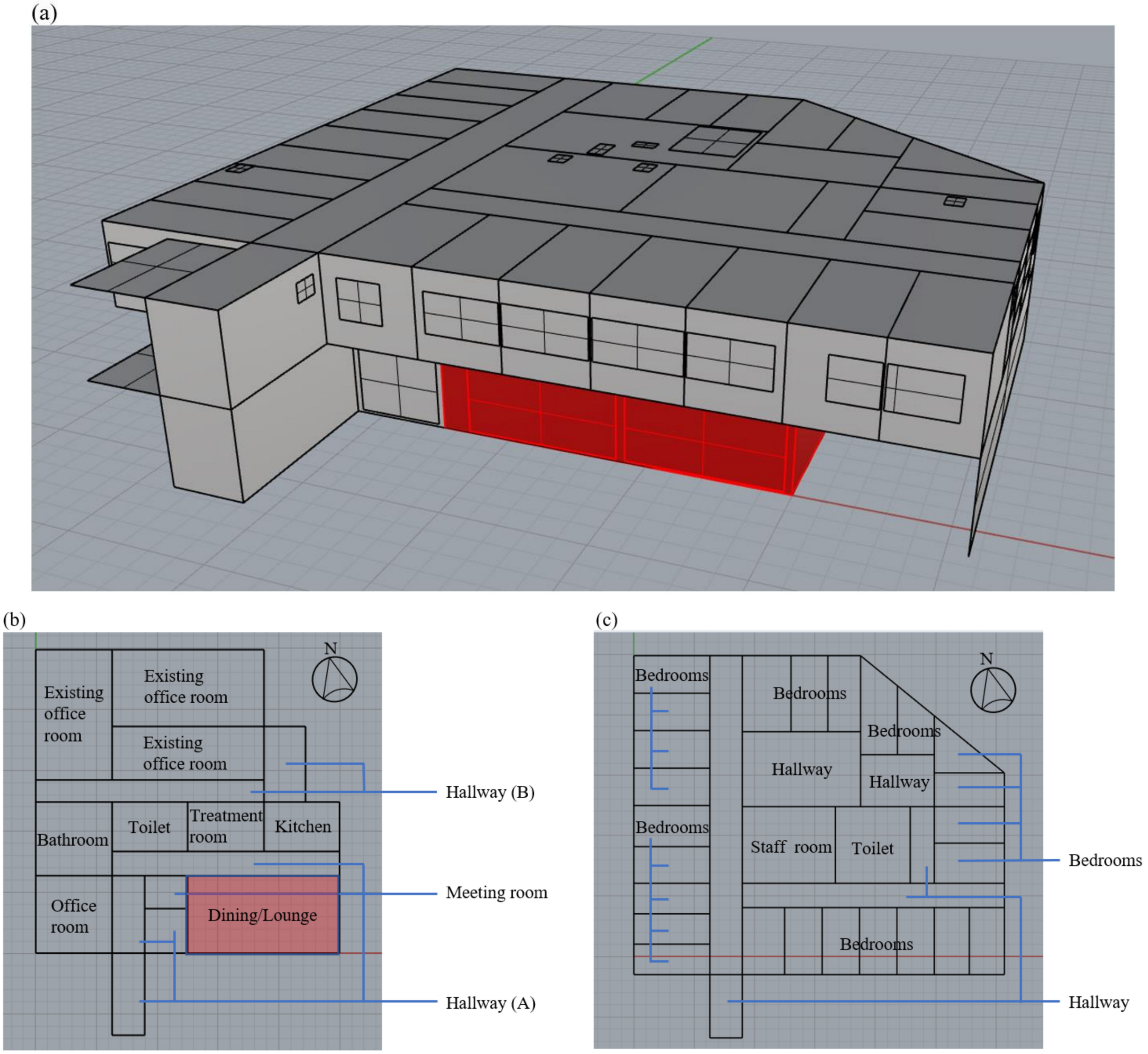


Figure 8. Building model in Rhinoceros: (**a**) 3D model of the nursing home (survey room in red); (**b**) floor plan of the first floor; (**c**) floor plan of the second floor.

Table 6. Maximum loads for caloric value of the human body, lighting design level, and electric equipment level for each zone.

Zone Type	Caloric Value of Human Body per Unit Area (W/m^2)	Number of People per Unit Area (Person/m^2)	Design Level per Unit Area [a] (W/m^2)	Design Level per Unit Area [b] (W/m^2)	Floor Area (m^2)
Dining/Lounge	59.5	0.50	20.0	0.0	79.33
Office room	23.8	0.20	20.0	15.0	39.96
Kitchen	11.9	0.10	20.0	10.0	25.11
Bathroom	7.4	0.08	12.0	3.0	38.07
Treatment room	23.8	0.20	20.0	15.0	25.49
Meeting room	23.8	0.20	20.0	15.0	9.50
Existing office room	11.9	0.10	12.0	12.0	200.88
Bedrooms	6.4	0.07	15.0	4.0	449.99
Staff room	7.4	0.08	12.0	3.0	49.02
Toilet	6.0	0.05	20.0	0.0	64.48
Hallway	6.0	0.05	20.0	0.0	368.27

Remarks: [a] Maximum design lighting levels for each zone type. [b] Total heat gains from electric equipment in each zone.

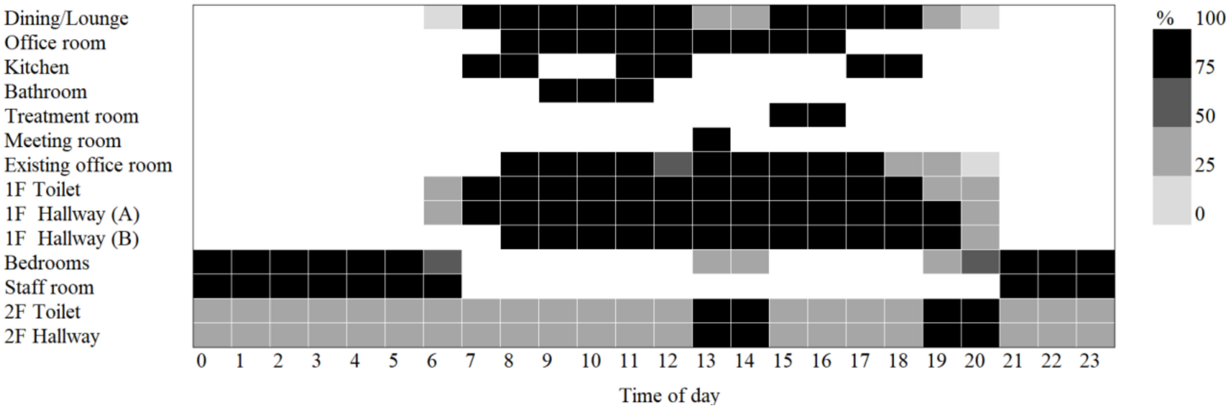


Figure 9. General occupancy pattern in the building zones.

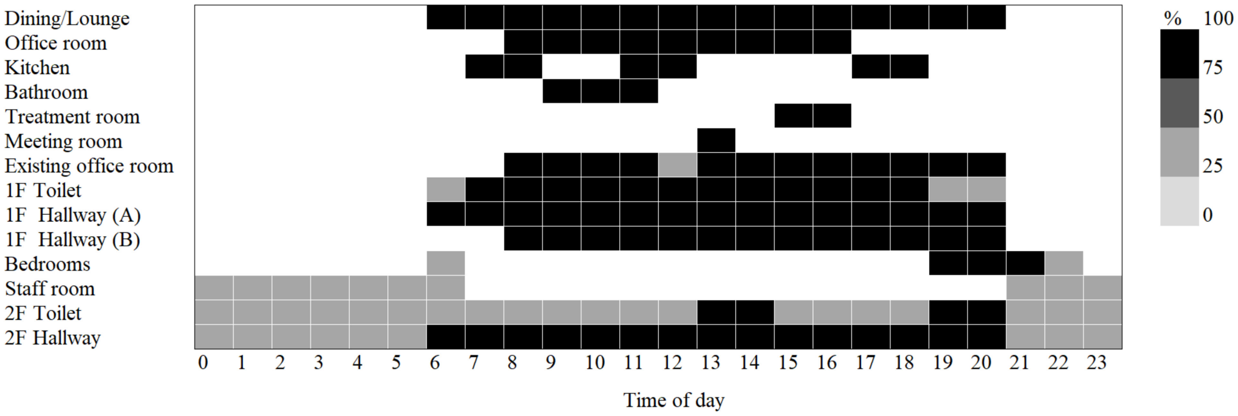


Figure 10. Electrical light schedule in each zone.

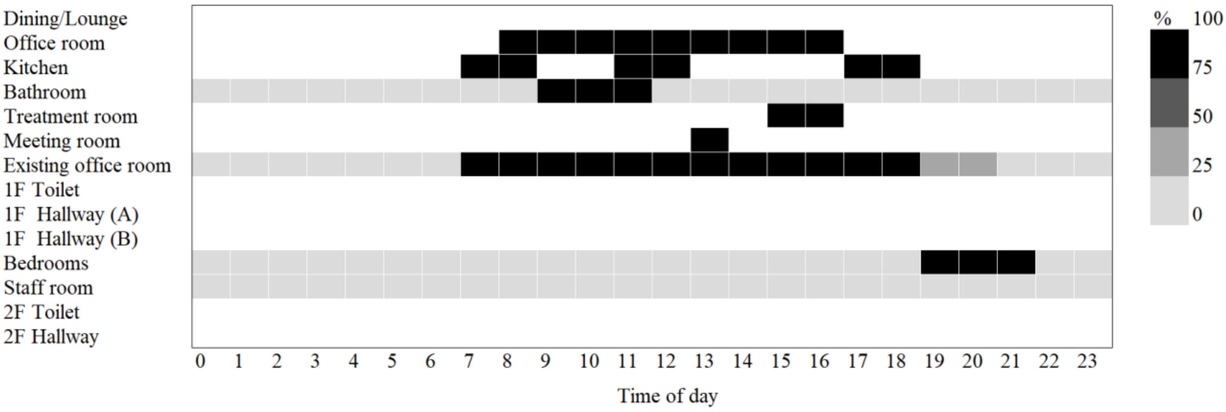


Figure 11. Electrical equipment schedule in each zone.

Heating and cooling operated in each zone. Two temperature ranges were set for heating and cooling: (1) a temperature range that considered the indoor temperature based on measured data, and (2) a temperature range that considered the improvement of occupants' thermal comfort and the control of health risks. The ventilation frequency was set to 4.0 air changes per hour in common spaces and 2.0 air changes per hour in other spaces including residents' bedrooms, referring to ASHRAE Standard 170 [62]. The windows were set to neither open nor close.

2. Construction System: The structural elements of the building and their respective characteristics are shown in Tables 7–9. There were three exterior walls and two roof configuration patterns, which were arranged according to the architectural drawings. Three types of U-values were established for windows, corresponding to (1) single-glazed glass + composite frame of resin and metal, (2) double-glazed glass (dry air) + metal frame, and (3) triple-glazed Low-E (gas) + composite frame of resin and metal, respectively [63]. To examine the effect of solar radiation in windows, (4) single-glazed glass + composite frame of resin and metal + heat shield film [64] was added to the comparison. The *U*-values and solar heat gain coefficients (SHGC) of the windows are shown in Table 10.

Table 7. Thermal properties of wall construction.

Element	Description	Thickness (mm)	k (W/(m·K))	ρ (kg/m^3)	c_p (J/(kg·K))	Solar Absorptance (–)	Visible Absorptance (–)	*R*-Value ((m^2·K)/W)	*U*-Value (W/(m^2·K))
Exterior wall 1	Layer 1	125	0.17	600	1100	–	–	–	1.26
	Layer 2	12.5	0.17	910	1100	–	–	–	
Exterior wall 2	Layer 1	2	15	7400	470	0.44	0.23	–	0.32
	Layer 2	12.5	0.17	910	1100	–	–	–	
	Layer 3	30	0.064	290	1420	–	–	–	
	air gap	–	–	–	–	–	–	0.15	
	Layer 5	50	0.042	24	840	–	–	–	
	Layer 6	12.5	0.17	910	1100	–	–	–	
Exterior wall 3	Layer 1	0.5	45	7900	460	0.44	0.30	–	0.24
	Layer 2	34.2	0.023	35	1700	–	–	–	
	Layer 3	100	0.042	24	840	–	–	–	
	Layer 4	12.5	0.17	910	1100	–	–	–	

Table 7. *Cont.*

Element	**Description**	**Thickness (mm)**	**k (W/(m·K))**	**ρ (kg/m^3)**	**c_p (J/(kg·K))**	**Solar Absorptance (–)**	**Visible Absorptance (–)**	**R-Value ((m^2·K)/W)**	**U-Value (W/(m^2·K))**
Interior wall	Layer 1	22	0.17	910	1100	–	–	–	2.45
	air gap	–	–	–	–	–	–	0.15	
	Layer 3	22	0.17	910	1100	–	–	–	

k: thermal conductivity, ρ: density, c_p: specific heat.

Table 8. Thermal properties of roof construction.

Element	**Description**	**Thickness (mm)**	**k (W/(m·K))**	**ρ (kg/m^3)**	**c_p (J/(kg·K))**	**Solar Absorptance (–)**	**Visible Absorptance (–)**	**R-Value ((m^2·K)/W)**	**U-Value (W/(m^2·K))**
Roof 1	Layer 1	65	1.4	2200	880	–	–	–	0.38
	air gap	–	–	–	–	–	–	0.18	
	Layer 3	100	0.042	24	840	–	–	–	
	Layer 4	9.5	0.17	910	1100	–	–	–	
Roof 2	Layer 1	0.8	45	7900	460	0.44	0.30	–	14.67
	Layer 2	3	0.044	50	1300	–	–	–	

k: thermal conductivity, ρ: density, c_p: specific heat.

Table 9. Thermal properties of floor construction.

Element	**Description**	**Thickness (mm)**	**k (W/(m·K))**	**ρ (kg/m^3)**	**c_p (J/(kg·K))**	**Solar Absorptance (–)**	**Visible Absorptance (–)**	**R-Value ((m^2·K)/W)**	**U-Value (W/(m^2·K))**
1F Floor	Layer 1	25	0.037	28	1300	–	–	–	1.36
	Layer 2	200	1.4	2200	880	–	–	–	
	Layer 3	2	0.19	1300	1200	–	–	–	
2F Floor	Layer 1	9.5	0.17	910	1100	–	–	–	0.37
	Layer 2	100	0.042	24	840	–	–	–	
	air gap	–	–	–	–	–	–	0.18	
	Layer 4	65	1.4	2200	880	–	–	–	
	Layer 5	2	0.19	1300	1200	–	–	–	
Exposed floor	Layer 1	0.8	210	2700	880	0.45	0.09	–	0.38
	Layer 2	100	0.042	24	840	–	–	–	
	air gap	–	–	–	–	–	–	0.18	
	Layer 4	65	1.4	2200	880	–	–	–	
	Layer 5	2	0.19	1300	1200	–	–	–	

k: thermal conductivity, ρ: density, c_p: specific heat.

2.2.4. Comparison Analysis

Heat load simulations in this study aimed to quantitatively evaluate the effects of windows insulation and solar shielding on the reduction of heat load, in addition to future forecasts of the total heat load in the common spaces of the target building. Therefore, a comparative analysis of graphs was conducted for sixty-four cases including eight climatic conditions, two heating and cooling setpoints, and four types of window performance from 2020 to 2050. In addition, future forecasts for each of the heating loads and the cooling loads were analyzed to clarify the ratio of heating and cooling loads.

Table 10. Window type and physical parameters.

Window Type	U-Value (W/(m^2·K))	SHGC (–)
(1) Single-glazed glass + Hybrid frame	5.8	0.70
(2) Double-glazed glass (dry air) + Metal frame	3.9	0.63
(3) Triple-glazed Low-E glass (gass) + Hybrid frame	1.9	0.26
(4) Single-glazed glass + Hybrid frame + Heat shield film	5.8	0.35

SHGC: Solar heat gain coefficient.

3. Results and Discussion

3.1. Measured Results of Thermal Comfort

Table 11 shows the results of the survey on the thermal environment and the subjective vote survey. Figure 12 shows the statistical distribution of operative temperature, HR, and running mean outdoor temperature at the time of the subjects' votes. Figure 12a–c show the results of the summer survey and Figure 12d–f show the results of the winter survey. Each bar chart of the operative temperature and running mean outdoor temperature indicates the number of data binned by 1 °C intervals and each bar chart of HR indicates the number of data binned by 1 g/kg (DA) intervals.

Table 11. Statistical summary of thermal environment data and thermal comfort indices.

(a) Summer							
	Unit	**Number**	**Mean**	**S.D.**	**Min.**	**Max.**	**Median**
t_a	°C	4633	25.0	1.4	20.7	27.6	25.5
t_g	°C	4633	24.6	1.6	20.0	27.4	25.1
t_r	°C	4633	24.6	1.6	19.8	27.4	25.1
HR	g/kg(DA)	4633	13.2	3.6	4.6	18.7	13.7
RH	%	4633	62	13	25	83	64
V	m/s	1	0.09	–	0.01	0.23	–
Met (residents)	met	4535	1.0	0.0	1.0	1.0	1.0
Met (staff)	met	29	1.5	0.2	1.2	1.6	1.6
I_{cl} (residents)	clo	4535	0.59	0.09	0.36	1.20	0.59
I_{cl} (staff)	clo	98	0.52	0.07	0.44	0.59	0.59
TSV (residents)	–	4535	0.0	0.2	−2	2	0
TSV (staff)	–	98	0.6	0.9	−2	3	1
TSV$_\mathrm{i}$	–	98	0.1	0.6	−1	2	0
PMV (residents)	–	4535	−0.1	0.6	−1.9	1.2	0.0
PMV (staff)	–	98	0.4	0.3	−0.3	1.0	0.4
t_o	°C	4633	24.8	1.5	20.4	27.4	25.3
ET*	°C	4633	25.0	1.7	20.4	28.1	25.5
Δt_a	°C	4633	0.5	0.4	−0.1	3.7	0.5
t_{out}	°C	4633	20.5	5.6	2.0	35.0	21.6
t_{rm}	°C	4633	16.5	3.8	7.6	22.4	17.3

Table 11. *Cont.*

(b) Winter							
	Unit	**Number**	**Mean**	**S.D.**	**Min.**	**Max.**	**Median**
t_a	°C	5631	22.5	1.6	17.4	27.1	22.6
t_g	°C	5631	21.0	1.8	15.2	26.4	21.1
t_r	°C	5631	20.9	1.8	15.1	26.4	21.0
HR	g/kg(DA)	5631	5.3	1.5	2.3	13.2	5.0
RH	%	5631	30	7	15	62	28
V	m/s	1	0.03	–	0.00	0.20	–
Met (residents)	met	5482	1.0	0.0	1.0	1.0	1.0
Met (staff)	met	59	1.4	0.2	1.2	1.6	1.6
I_{cl} (residents)	clo	5482	1.05	0.20	0.59	2.02	0.93
I_{cl} (staff)	clo	149	0.88	0.12	0.59	0.93	0.93
TSV (residents)	–	5482	−0.1	0.3	−2	1	0
TSV (staff)	–	149	0.0	0.7	−1	1	0
TSV_i	–	149	−0.2	0.4	−1	0	0
PMV (residents)	–	5482	−0.5	0.5	−2.4	0.9	−0.5
PMV (staff)	–	149	0.3	0.3	−0.5	1.1	0.3
t_o	°C	5631	21.7	1.7	16.6	26.7	21.8
ET*	°C	5631	21.3	1.7	16.1	26.1	21.5
Δt_a	°C	5631	1.7	1.2	−1.2	5.3	1.8
t_{out}	°C	5631	4.2	5.7	−6.3	23.0	3.7
t_{rm}	°C	5631	4.2	3.5	−1.7	11.0	3.8

t_a: indoor air temperature, t_g: globe temperature, t_r: mean radiant temperature, HR: humidity ratio, RH: relative humidity, V: air velocity, *Met*: metabolic rate, I_{cl}: clothing insulation, TSV: thermal sensation vote, TSV_i: imaginal thermal sensation vote, PMV: predicted mean vote, t_o: operative temperature, ET*: new effective temperature, Δt_a: vertical air temperature difference, t_{out}: outdoor air temperature, t_{rm}: running mean outdoor temperature.

The indoor operative temperature in summer ranged from 20.4 to 27.4 °C, with a mean value of 25.3 °C. In winter, the indoor operative temperature ranged from 16.6 to 26.7 °C with a mean of 21.8 °C. Most of the operative temperature data ranged from 17 to 28 °C as defined by the Japanese act on maintenance of sanitation in buildings [65]; however, 0.2% of the data from the winter survey were below the lower limit criteria. ET* in summer ranged from 20.4 to 28.1 °C, with a mean value of 25.5 °C. In winter, ET* ranged from 16.1 to 26.1 °C, with a mean value of 21.5 °C. A possible cause of local discomfort for the subjects is the vertical temperature difference (Δt_a). In this study, Δt_a was calculated from the difference between the air temperature at 1.1 m above the floor and the air temperature at 0.1 m above the floor, assuming the head position when sitting in a chair. The mean value of Δt_a was 0.5 °C in summer and 1.7 °C in winter. The maximum values of Δt_a were 3.7 °C in summer and 5.3 °C in winter, exceeding the temperature difference within 3 °C recommended by ISO 7730 [49]. The mean HR was 13.2 g/kg (DA) in summer and 5.3 g/kg (DA) in winter. The RH in winter averaged 31%, which was lower than the lower limit of 40% set by the Japanese act on maintenance of sanitation in buildings [65]. The average air velocity was less than 0.20 m/s in both summer and winter. These values meet the application of the analytical comfort zone method of ASHRAE Standard-55 [47].

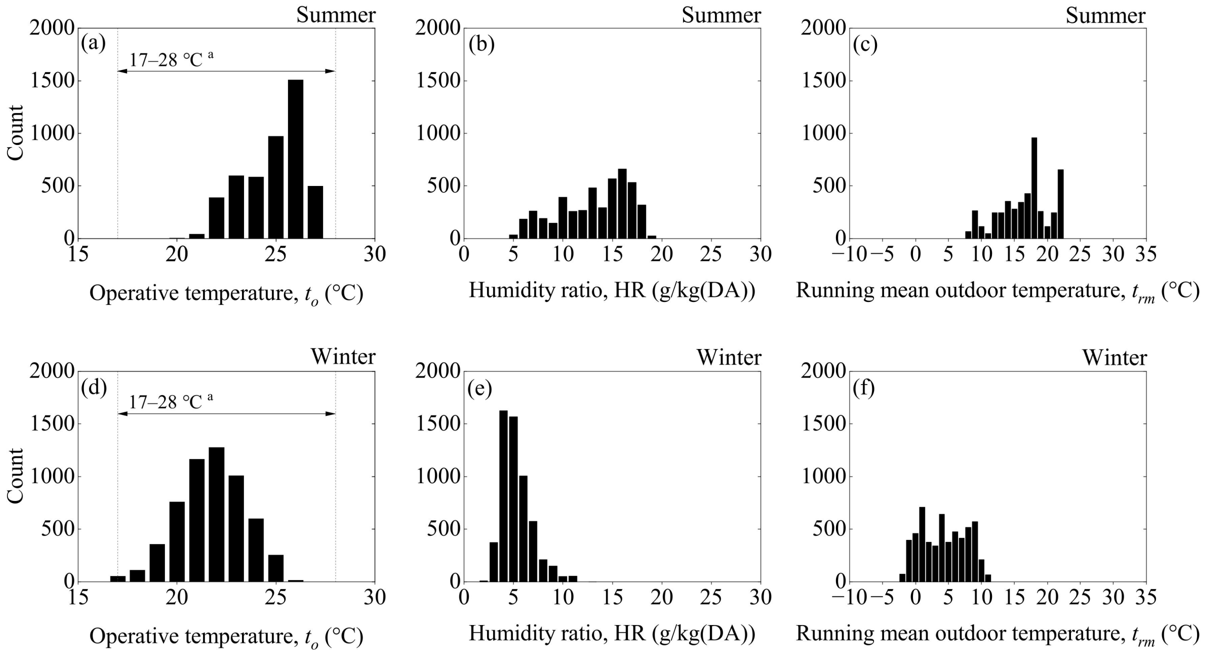


Figure 12. Histogram of environmental data at the time of subjective votes: (**a**) operative temperature, (**b**) running mean outdoor temperature and (**c**) humidity ratio in summer and (**d**) operative temperature, (**e**) running mean outdoor temperature and (**f**) humidity ratio in winter. Remark: [a] Japanese act on maintenance of sanitation in buildings, law number: Act No. 20 of 1970, the temperature ranges from 17 to 28 °C.

The mean metabolic rate of the staff was 1.5 met in summer and 1.4 met in winter. This is a work intensity equivalent to light work indoors. The mean clothing insulation worn by residents was 0.59 clo in summer and 1.05 clo in winter. The mean clothing insulation worn by staff was 0.52 clo in summer and 0.88 clo in winter. The resident's clothing insulation in summer was 0.09 clo higher and the staff's clothing insulation was 0.02 clo higher than the general estimate for adult office workers in summer (0.50 clo) [47]. The clothing insulation worn by residents in winter was 0.05 clo higher than the general estimate for adult office workers in winter (1.00 clo) [46], whereas the clothing insulation worn by staff was 0.12 clo lower. The standard deviation of clothing insulation worn by residents was 0.09 clo in summer and 0.20 clo in winter. The standard deviation of clothing insulation worn by staff was 0.07 in summer and 0.12 in winter. Thus, both residents and staff tended to adjust their clothing more in winter than in summer, and this tendency was particularly pronounced for residents.

The mean TSV value for residents was 0.0 in summer and −0.1 in winter. The mean TSV value for staff was 0.6 in summer and 0.0 in winter; the mean value of TSV_i was 0.1 in summer and −0.2 in winter. The mean value of PMV for residents was negative, −0.1 in summer and −0.5 in winter. Conversely, the mean value of PMV for staff was positive, 0.4 in summer and 0.3 in winter.

3.2. Distribution of Thermal Sensation

Figure 13 shows the statistical distribution of TSV for residents and staff and TSV_i. Figure 12a–c show the results of the summer survey. In addition, Figure 13d–f show the results of the winter survey. The percentage of residents who voted their own thermal sensation as neutral (TSV = 0) was 97.5% in the summer and 91.7% in the winter. The percentage of staff who voted their own thermal sensation as neutral (TSV = 0) was 36.7% in summer and 57.1% in winter. The voting percentage of neutral (TSV_i = 0) in TSV_i was 76.5% in summer and 84.6% in winter. Comparing the TSV of residents with the TSV_i of staff, it can be confirmed that the staff expected the percentage of residents voting neutral to be lower than it actually was in both summer and winter. To examine the independence of the distributions of TSV and TSV_i of staff, a chi-square test was performed. Consequently, the two groups were statistically different ($p < 0.05$). This indicated that the sensation of the staff and the staff's expected thermal sensation of the residents had different distributions. In addition, because of the examination of the independence of the distribution of resident's TSV and TSV_i, it was shown that there were statistical differences between summer and winter ($p < 0.05$) and that the thermal sensation answered by residents and the thermal sensation expected by staff also had different distributions. The results of these chi-square tests suggest that although the staff answered the TSV_i with the expectation that her own thermal sensation and the residents' thermal sensation were different, it may be difficult to accurately predict the thermal sensation of residents.

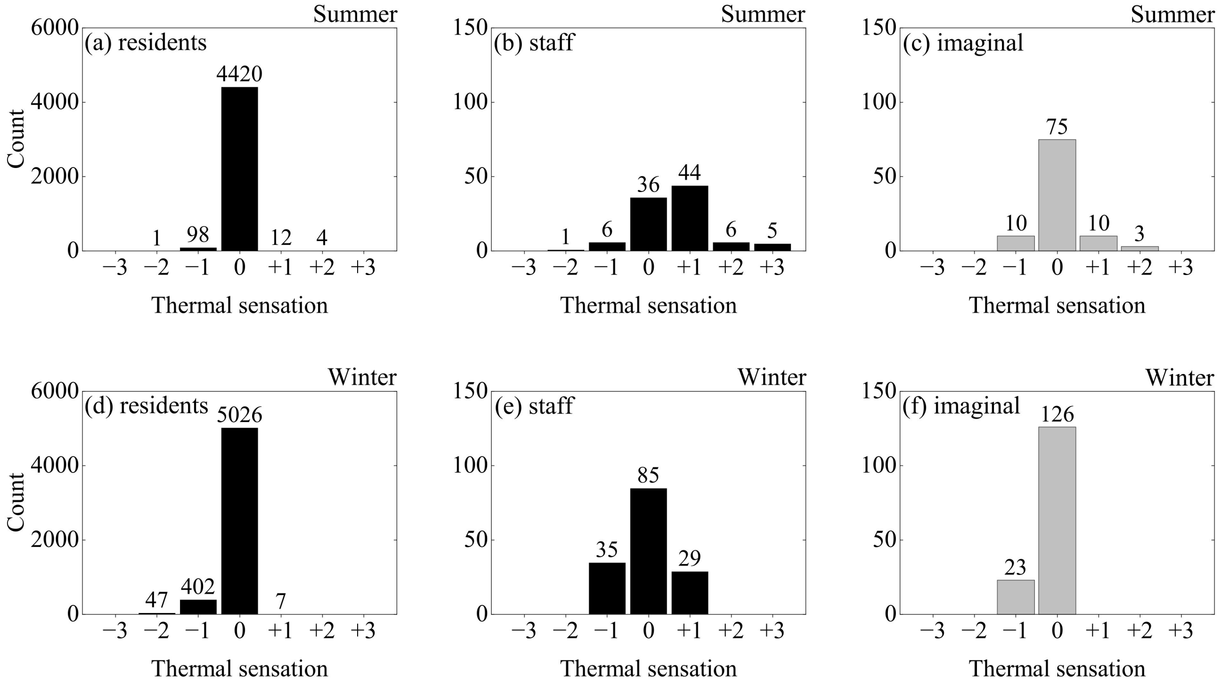


Figure 13. Histogram of subjective votes: TSV for (**a**) residents and (**b**) staff and (**c**) TSV_i in summer, and TSV for (**d**) residents and (**e**) staff and (**f**) TSV_i in winter.

On the seven-point thermal sensation scale, it can be assumed that people who vote on the central three categories (TSV = −1, 0, +1) are satisfied with their thermal environment [47]. Applying this assumption to the TSV in this study, over 80% of residents and staff were satisfied with the thermal environment of the common space throughout the year. In contrast, TSV = −2, −3, +2, and +3 voting represent thermal dissatisfaction. According to the TSV obtained in this study, the residents felt little thermal dissatisfaction (0.1% in summer and 0.9% in winter). In addition, staff felt approximately 10% thermal dissatisfaction in summer; however, they did not feel thermal dissatisfaction in winter (12.2% in summer and 0.0% in winter). These results indicate that the thermal environment in the common space in which the survey was conducted met the minimum standard of 80% acceptability recommended in ASHRAE Standard 55.

3.3. Linear Regression Analysis

A linear regression equation was created using the thermal sensation and the indoor operative temperature at the time of the subjects' votes. To clarify the trend of the regression equation, the regression equation was developed using the mean value of thermal sensation. The mean value of thermal sensation was binned by 0.5 °C intervals, and the regression equations were weighted according to the number of votes falling in each of the bins. To improve the prediction accuracy, bins that were less than 1% of the number of votes in each graph were excluded from the calculation of the regression equation. In this study, we focused on the neutral temperature, regression coefficient, and acceptable range of each regression equation. In this study, we also defined the neutral temperature estimated from TSV, TSV_i, and PMV as $t_{n,TSV}$, $t_{n,TSVi}$, and $t_{n,PMV}$ respectively.

3.3.1. Linear Regression of TSV and TSV_i

Figure 14 and Table 12 show the results of the regression analysis of TSV and TSV_i. Figure 13a TSV of residents, (b) TSV of staff, and (c) TSV_i results of the summer survey. In addition, Figure 13d TSV of residents, (e) TSV of staff, and (f) TSV_i results of the winter survey.

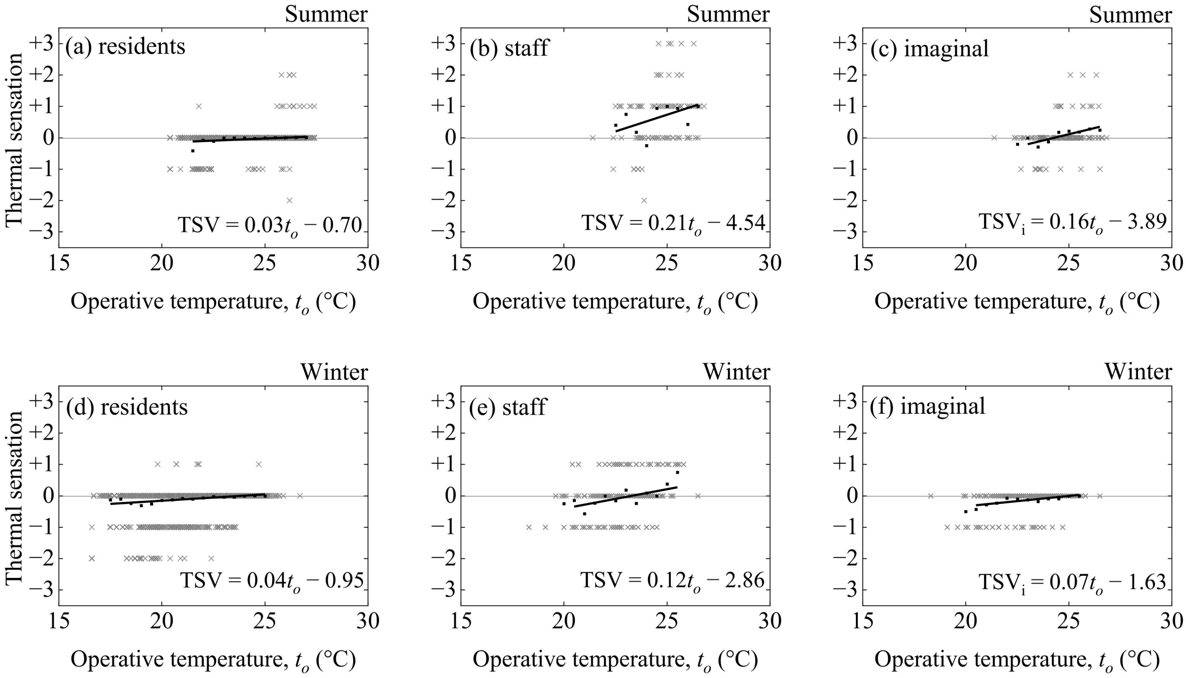


Figure 14. Linear regression of thermal sensation against indoor operative temperature: (**a**) TSV of residents, (**b**) TSV of staff, and (**c**) TSV_i results of the summer survey and (**d**) TSV of residents, (**e**) TSV of staff, and (**f**) TSV_i results of the winter survey.

Table 12. Regression equation, neutral temperature, and acceptable range (−0.85 < TSV < +0.85) in this study.

Season	Regression Equation	F	p	R^2	t_n (°C)	Acceptable Range (°C)
Summer	(1) TSV (residents) = $0.03t_o - 0.70$	5.6	<0.05	0.30	25.9	N.D.
	(2) TSV (staff) = $0.21t_o - 4.54$	3.1	$p = 0.12$	0.21	N.D.	N.D.–25.5
	(3) $TSV_i = 0.16t_o - 3.89$	15.7	<0.05	0.65	24.3	N.D.
Winter	(4) TSV (residents) = $0.04t_o - 0.95$	35.2	<0.05	0.70	23.8	N.D.
	(5) TSV (staff) = $0.12t_o - 2.86$	8.5	$p = 0.15$	0.41	23.8	N.D.
	(6) $TSV_i = 0.07t_o - 1.63$	16.0	<0.05	0.58	25.1	N.D.

t_n: neutral temperature, TSV: thermal sensation vote, TSV_i: imaginal thermal sensation vote. t_o: operative temperature.

The neutral temperature by linear regression method is calculated by substituting 0 for thermal sensation in the regression equation. The $t_{n,TSV}$ for residents were 25.9 °C in summer and 23.8 °C in winter. The $t_{n,TSV}$ for staff in summer was not estimated because it is an extrapolation. The $t_{n,TSV}$ for staff in winter was 23.8 °C, the same value as $t_{n,TSV}$ for residents in winter, indicating that residents and staff prefer the same indoor operative temperature in winter. The $t_{n,TSVi}$ in summer was 24.3 °C, which was 1.6 °C lower than the residents' $t_{n,TSV}$ in summer. In winter, the $t_{n,TSVi}$ was 25.1 °C, which was 1.3 °C lower than the $t_{n,TSV}$ for residents in winter. Therefore, it was confirmed that residents preferred higher indoor temperatures than those predicted by staff in both summer and winter. In this analysis, regression Equations (2) and (5) with TSV of staff did not meet statistical significance; thus, the results of the regression analysis with TSV of the staff should be interpreted as reference data only.

Table 13 shows the neutral temperature of elderly people calculated by linear regression in previous studies; Wu [66], Jiao [8], Tartarini [24], Tao [67], Forcada [21,22], and Jin [28] conducted field studies in elderly facilities, whereas Hwang [31], Wu [66], and Bills [68] conducted field research in residential homes. In addition, Fanger [69] and Xiong [19] conducted experimental studies. Three different thermal indices were employed in these studies: operative temperature, air temperature, and ambient temperature (t_{am}).

Previous studies by Jiao [8], Tao [67], Forcada [21,22], Hwang [31], and Bills [68] showed that the neutral temperature of elderly people differed between summer and winter. The largest seasonal difference was found by Jiao [8], who reported that the neutral temperature of the elderly varied by 9.3 °C throughout the year. The laboratory experiment of Xiong [19] and the field study of Jiao [8] were conducted in the same city of Shanghai, China. The neutral temperature of the elderly in summer was a difference of 0.6 °C; thus, the thermal neutrality of the elderly in the same area showed a close trend. Similarly, Tartarini [24] and Bills [68] conducted a summer study in Australia, according to their study, the neutral temperature of the elderly was 22.9 °C and 22.0 °C, respectively, which was lower than the results of summer studies in other regions. The summer study of Wu et al. [66] reported that the neutral temperature of the elderly had a difference of 3 °C between nursing homes and residential homes. Tao's summer survey showed a neutral temperature based on the temperature range of interpolation (23.9–26.8 °C) in the regression analysis because of the small gradient of thermal sensation against the operative temperature of the elderly [67]. The neutral temperature of this study in summer was the second highest after that of Tao [67] among the studies conducted in summer, as shown in Table 13. The neutral temperature of this study in winter was 23.8 °C, the highest among the studies conducted in winter, as shown in Table 13, which was 2.2 °C and 1.1 °C higher than the neutral temperatures of Forcada et al. [22] and Jin et al. [28], who conducted their studies in AC-mode elderly care facilities. In summary, the neutral temperature of the residents in this study showed a tendency to perceive the hotter side of the indoor temperature as neutral in both summer and winter compared to the neutral temperature of the elderly in previous studies.

The gradient of the thermal sensitivity to the indoor temperature indicates the thermal sensitivity of the subject. Thermal sensitivity is the degree to which a person perceives indoor temperature [70]. The magnitude of the value of the regression coefficient can be interpreted as indicating the high thermal sensitivity of the subject [8]. In addition, the gradient of thermal sensitivity to indoor temperature represents the subject's thermal adaptation to the thermal environment; thermal adaptation is the degree to which a person adjusts and adapts to fluctuations in indoor temperature to achieve thermal comfort [71]. In the theory of adaptive thermal comfort, the magnitude of the value of the regression coefficient is negatively related to the thermal adaptation of the subject [72]. If the regression coefficient is interpreted as a measure of thermal adaptation, the winter staff shown in Figure 13e can be estimated to be approximately 1.8 times more adaptable than the summer staff shown in Figure 13b. In addition, as shown in Figure 13a,d, the residents showed little change in the thermal sensation scale for indoor temperature changes of 21.5–27.0 °C in summer and 17.5–25.0 °C in winter, indicating that they were acclimatized to the indoor thermal environment. Conversely, when the regression coefficients were interpreted as indicators of thermal sensitivity, the thermal sensitivity of the residents shown in Figure 13a,d were significantly lower than that of the staff shown in Figure 13b,e, indicating that residents were not sensitive to changes in indoor temperature.

Table 13. Comparison of neutral temperature for the elderly using the regression method.

Study	Survey Tear	Location	Climate	Survey Type	Building Type	Ventilation Type	Season	Age Group	Sample Size	Regression Equation	t_n (°C)
This study	2020–2021	Nagano, Japan	Cfa	field survey	care facility	AC	Summer	69–96	4535	$\text{TSV} = 0.03t_o - 0.70$	25.9
							Winter	69–96	5482	$\text{TSV} = 0.04t_o - 0.95$	23.8
Y. Wu [66]	2012	Chongqing, China	Cfa	field survey	care facilities	NV	Summer	60–100	119	$\text{TSV} = 0.13t_a - 3.2$	25.4
Y. Jiao [8]	2014–2017	Shanghai, China	Cfa	field survey	care facilities	NV	Summer	aged 70+	330	$\text{TSV} = 0.12t_o - 3.15$	25.4
							Winter	aged 70+	342	$\text{TSV} = 0.08t_o - 1.27$	16.8
							Mid-season	aged 70+	368	$\text{TSV} = 0.04t_o - 0.94$	26.1
F. Tartarini [24]	2015–2016	southeast NSW, Australia	Cfa, Cfb	field survey	care facilities	AC and NV	Summer	–	322	–	22.9
Y. Tao [67]	2015–2016	Hong Kong	Cwa	field survey	care facilities	AC and NV	Summer	aged 65+	181	–	23.9–26.8
							Winter	aged 65+	213	–	22.7
N. Forcada [21]	2019	Barcelona, Tarragona, and Valencia, Spain	Csa	field survey	care facilities	–	Summer	46–99	480	$\text{TSV} = 0.28t_o - 7.17$	25.3
N. Forcada [22]	2019	Barcelona, Tarragona, and Valencia, Spain	Csa	field survey	care facilities	AC	Winter	65–99	724	$\text{TSV} = 0.12t_o - 2.48$	21.6
Y. Jin [28]	–	Edinburgh, Scotland, UK	Cfb	field survey	care facility	AC	Winter	83–94	–	–	22.7
R.-L. Hwang [31]	2007	Taiwan	–	field survey	home	AC and NV	Summer	60–82	160	$\text{TSV} = 0.39t_o - 9.84$	25.2
							Winter	60–82	192	$\text{TSV} = 0.28t_o - 6.50$	23.2
Y. Wu [66]	2012	Chongqing, China	Cfa	field survey	home	AC	Summer	60–94	333	$\text{TSV} = -0.07t_a + 3.3$	–
						NV	Summer			$\text{TSV} = 0.10t_a - 2.3$	22.4
R. Bills [68]	2015–2016	Adelaide, Australia	Csa	field survey	home	AC and NV	Summer	aged 65+	2647	$\text{TSV} = 0.14t_o - 2.97$	22.0
							Winter	aged 65+		$\text{TSV} = 0.28t_o - 5.50$	19.7
P. O. Fanger [69]	1968	Copenhagen, Denmark	Cfb	chamber experiment	–	–	Autumn	68.0 ± 4.7 [a]	128	$\text{TSV} = 0.32t_{am} - 4.24$	25.7
J. Xiong [19]	2016	Shanghai, China	Cfa	chamber experiment	–	–	Summer	aged 70+	–	–	26.0

t_n: neutral temperature, AC: air-conditioned, NV: naturally ventilated, t_o: operative temperature, t_a: indoor air temperature, t_{am}: ambient temperature. Remark: [a] mean ± standard deviation.

The results in Table 12 show that the regression coefficients for residents who participated in this study were smaller than those for staff. According to a review article on thermal sensitivity in the elderly written by Guergova et al. [73], they concluded that thermal sensitivity gradually decreases with age, and both warm and cold sensitivity decrease; however, the ability to perceive warm stimuli decreases more significantly. The results of this study support the assertions of previous studies investigating thermal sensitivity in the elderly. Conversely, according to the regression analysis of the previous studies in Table 13, the thermal sensitivity of the elderly reported a tendency to decrease in winter than in summer [8,21,22,31]. The reason why the regression coefficients in the summer survey are larger than those in the winter survey may be explained by clothing adjustment. Nakagawa et al. [74] investigated the limits of clothing adjustment in a hot environment for students at a high school in Nagano City, the same target area as the present study. Consequently, it was confirmed that the clothing insulation decreased and converged with an increase in indoor operative temperature. In an analysis that included survey data from previous studies, the authors reported that convergence values for the clothing insulation were obtained above 29 °C. White-Newsome et al. [33] investigated the occupant behaviors of elderly residents in 29 homes in Detroit, USA, in an environment with high indoor temperatures. There was a statistically significant increase in clothing changes ranging from 24.4 to 26.6 °C. A trend toward fewer occupant behaviors to hot temperatures were reported when the indoor temperature was above 29.4 °C. Because the maximum indoor operative temperature during the summer in this study was 27.4 °C, it is likely that the temperature was within the range of indoor temperatures to which the residents could adapt by adjusting their clothing.

The acceptable range as given in ASHRAE Standard 55 is calculated by substituting ± 0.85 for the thermal sensation in the regression equation [72]. The width of the acceptable temperature range estimated by linear regression analysis is proportional to the low slope of the regression equation. For the residents who participated in this study, it was not possible to estimate the receptive range in both summer and winter because the gradient of the indoor operative temperature for thermal sensation was low. In addition, the number of votes from staff obtained in this study was limited compared to that of residents. The indoor temperature range observed in the survey room was relatively narrow because the room under investigation was controlled by air conditioning. Consequently, the acceptable range for the staff was also extrapolated and therefore was not estimated. From the staff regression Equation (2) for the summer survey, only the upper limit of the 80% acceptability limit could be estimated, and this value was 25.5 °C.

3.3.2. Linear Regression of PMV

Figure 15 and Table 14 show the results of the regression analysis of PMV. All regression equations met statistical significance ($p < 0.05$). Figure 14a residents and Figure 14b staff show the results from the summer survey. In addition, Figure 14c (residents) and Figure 14d (staff) show the results from the winter survey.

Focusing on the regression lines of the residents shown in Figure 15a,c, the regression lines of PMV and TSV intersected at 25.1 °C in summer and 23.7 °C in winter. It was also confirmed that PMV overestimated the TSV of the residents as the indoor operative temperature moved away from the respective intersection points. As shown in Tables 12 and 14, the difference between $t_{n,PMV}$ and $t_{n,TSV}$ for residents was less than 1 °C in both summer and winter. The 80% acceptable range estimated from PMV = ± 0.5 could be calculated only for residents in the summer study. This temperature ranged from 23.8 to 26.6 °C.

Focusing on the staff regression lines shown in Figure 15b,d, PMV predicted a lower thermal sensation than TSV in summer and a higher thermal sensation in winter. As shown in Figure 15b, the slope of the regression equation for PMV in summer approximated the slope of the regression equation for TSV in summer; however, PMV had a scale of approximately 0.3 lower than TSV under the same temperature conditions. The $t_{n,PMV}$ for staff were 22.7 °C in summer and 21.2 °C in winter. Comparing $t_{n,TSV}$ for staff and $t_{n,PMV}$ for staff in winter, $t_{n,PMV}$ was 2.6 °C lower than $t_{n,TSV}$.

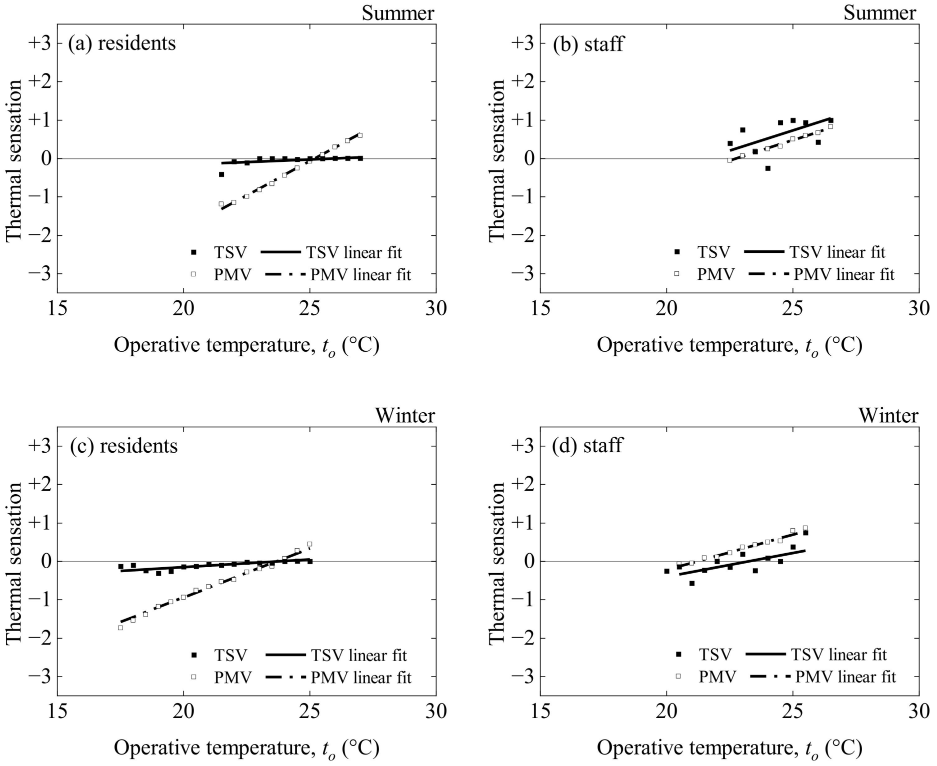


Figure 15. Linear regression of TSV and PMV against indoor operative temperature: (**a**) residents and (**b**) staff in summer and (**c**) residents and (**d**) staff in winter.

Table 14. Regression equation, neutral temperature, and acceptable range (−0.5 < PMV < +0.5) in this study.

Season	Regression Equation	F	p	R^2	t_n (°C)	Acceptable Range (°C)
Summer	(7) PMV (residents) = $0.36t_o - 9.00$	3409.9	<0.05	1.00	25.2	23.8–26.6
	(8) PMV (staff) = $0.21t_o - 4.82$	364.1	<0.05	0.98	22.7	N.D.–25.1
Winter	(9) PMV (residents) = $0.26t_o - 6.04$	1070.8	<0.05	0.99	23.7	21.7–N.D.
	(10) PMV (staff) = $0.18t_o - 3.90$	260.2	<0.05	0.96	21.2	N.D.–23.9

t_n: neutral temperature, PMV: predicted mean vote, t_o: operative temperature.

In summary, PMV is effective in predicting the thermal neutrality of the residents in this study; however, the sensitivity of thermal sensation to the operative temperatures is different between PMV and TSV. In contrast, PMV predicted the thermal neutrality of the staff in the present study to the lower temperature side in summer and to the higher temperature side in winter; however, the sensitivity of thermal sensation to the operative temperatures showed a similar trend between PMV and TSV.

3.4. Comfort Zone

Using the analytical comfort zone method of ASHRAE Standard 55 [47], the acceptable range for each subject in summer and winter was calculated. Because the boundary of the acceptable range predicted by this method is determined by the temperature and humidity, it is shown on the psychrometric chart. Figure 15 shows the measured data at the time of subjects' votes and the 80% acceptability limit for each subject calculated using the analytical comfort zone method. Figure 16a (resident) and Figure 16b (staff) show the results of the summer survey. In addition, Figure 16c (resident) and Figure 16d (staff) show the results of the winter survey.

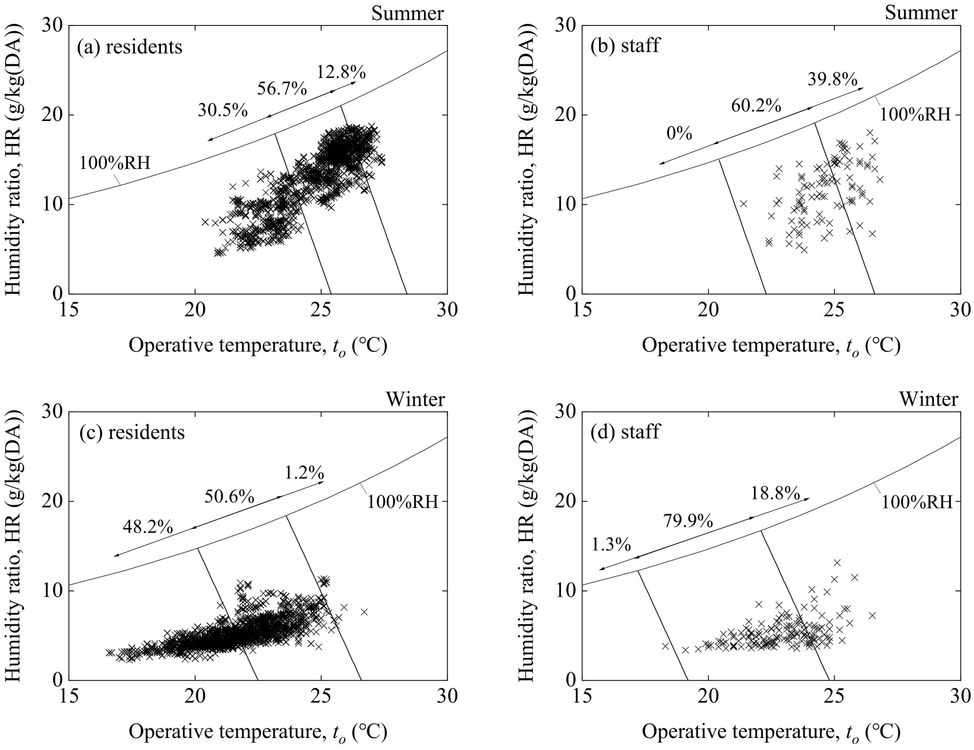


Figure 16. Scatter plot of indoor operative temperature compared with 80% thermal acceptability limits for each subject calculated using the analytical comfort zone method: (**a**) residents and (**b**) staff in summer and (**c**) residents and (**d**) staff in winter.

From the analysis in Section 3.2, residents voted 99.9% of TSV in summer and 99.1% of TSV in winter to the central three categories. Therefore, it is expected that most of the measured data plotted on the psychrometric chart are included in the acceptable temperature range. However, as shown in Figure 16a,c, the percentage of measurement data at the time of voting that fell within the acceptable range was 56.7% in summer and 50.6% in winter, both of which were approximately half. The proportion of measurement data that exceeded the acceptable range at the time of voting was distributed in the range below the lower limit of the acceptable range in both summer and winter.

From the analysis in Section 3.2, the staff voted 87.8% of TSV in summer and 100% in winter to the central three categories. However, as shown in Figure 16b,d, the percentage of measurement data at the time of voting that fell within the acceptable range was 60.2% in summer and 79.9% in winter. It was confirmed that the proportion of the measurement data exceeding the acceptable range was distributed in the range exceeding the upper limit of the acceptable range in both summer and winter.

In Figure 16a–d, it was confirmed that many votes that met thermal comfort were reported in environments with lower temperature and lower humidity or higher temperature and higher humidity than the 80% acceptability limit calculated using the analytical comfort zone method. These results indicate that the residents and staff who participated in this study may have accepted a wider temperature range than the PMV-based acceptable range.

3.5. Adaptive Thermal Comfort Model

In the previous studies on elderly facilities, analyses were conducted to examine the relationship between the outdoor environment and thermal comfort for NV mode [10,70] and AC mode [22,66]. In this study, the indoor thermal environment was evaluated by comparing the measured data with the adaptive model of ISO 17772-1 [57] (Figure 17). Figure 16a (residents) and Figure 16b (staff) show the results of the summer survey. In addition, Figure 16c (resident) and Figure 16d (staff) show the results of the winter survey. Figure 17a,c show the 90% acceptability limit for comparison in addition to the 80% acceptability limit because the residents (elderly) participating in this study fell into the Category I recommended target group.

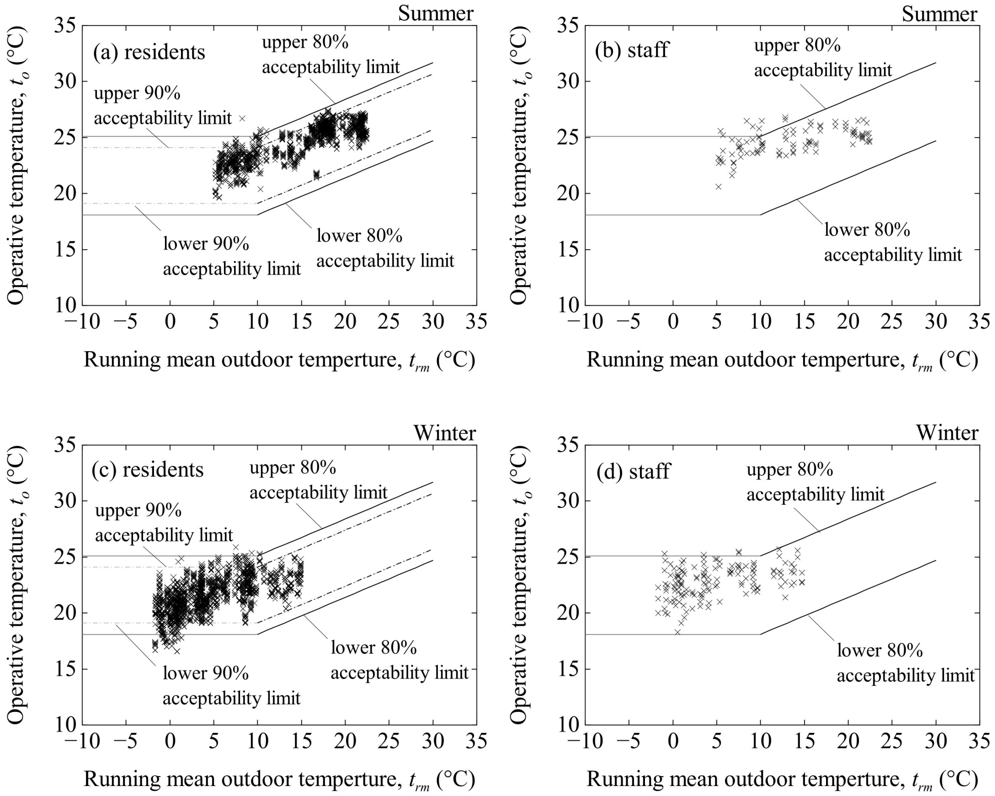


Figure 17. Scatter plot of indoor operative temperature compared with ISO 17772-1′s 80% and 90% adaptive thermal acceptability limits: (**a**) residents and (**b**) staff in summer and (**c**) residents and (**d**) staff in winter.

The adaptive model in ISO 17772-1 shows the outdoor temperature conditions ranging from 10 to 30 °C. Conversely, the running mean outdoor temperature in Nagano City during this study period ranged from 5.2 to 22.4 °C in summer and −1.7 to 14.9 °C in winter. Consequently, the outdoor temperature data used in this study were 9.6% below the lower limit of the applicable range of the adaptive model in summer and 97.0% below the lower limit in winter. The tendency for outdoor temperature data to be below the lower limit of the adaptive model's range of applicability was also confirmed in a study by Jiao et al. [70], who conducted a survey in an elderly care facility in Shanghai, China. In this study, referring to the previous study by Bienvenido-Huertas [75], the acceptable range below t_{rm} = 10 °C was independent of the outdoor temperature, and a fixed value corresponding to the limit of the adaptive model was set.

Table 15 shows the number of voting that exceeded the 80% acceptability limit of the adaptive model. The percentage of measured data that exceeded the 80% acceptability limit of the adaptive model at the voting time in this study was less than 10% in both summer and winter. The highest percentage of measured data exceeding the acceptability limit is shown in Figure 17b, which is 6.0% above the upper limit of the acceptability limit. The only data below the lower limit of the acceptability limit were reported by the residents of the winter survey (2.4%). Table 16 shows the number of voting in which the residents' voting exceeded the 90% acceptability limit of the adaptive model. The percentage of measured data included within the acceptable range at the voting time was 97.4% in summer and 85.8% in winter. This result is relatively close to the percentage of tenants who reported TSV as neutral (TSV = 0).

Table 15. Percentage of subjective votes exceeding the 80% adaptive thermal acceptability limits of ISO 17772-1.

Season	Attribute	Sample Size	Above Upper 80% Limit		Below Lower 80% Limit	
			Number	Percent	Number	Percent
Summer	residents	4535	0	0.0	0	0.0
	staff	98	4	4.1	0	0.0
Winter	residents	5482	83	1.5	127	2.4
	staff	149	9	6.0	0	0.0

Table 16. Percentage of subjective votes of residents exceeding the 90% adaptive thermal acceptability limit of ISO 17772-1.

Season	Sample Size	Above Upper 90% Limit		Below Lower 90% Limit	
		Number	Percent	Number	Percent
Summer	4535	119	2.6	0	0.0
Winter	5482	396	7.2	381	7.0

The trends in Tables 15 and 16 were relatively consistent with the trends in residents' thermal dissatisfaction obtained from the TSV distribution in Section 3.2. This suggests that the adaptive model in ISO 17772-1 may be closer to the thermal comfort of the residents than the comfort zone in Section 3.4. In contrast, the adaptive model was found to differ from the trend of thermal dissatisfaction based on the TSV of the staff in the summer. The staff was often doing light work just before conducting her own subjective survey. Thus, it is possible that the staff expressed dissatisfaction with a higher indoor operative temperature compared to the acceptable range indicated by the adaptive model.

3.6. Health Risks and Thermal Comfort

The findings related to health risks in indoor thermal environments are summarized and shown on the psychrometric chart in Figure 18. In addition, Figure 18a–d show the 80% acceptability limit (comfort zone) for each subject shown in Section 3.4 and the indoor temperature range (21–24 °C) recommended for nursing homes in ASHRAE Standard 170-2017 [76] and compared to the warning line for health risk.

The guideline to prevent heat stroke published by the Japanese Society for Biometeorology [77] uses the wet bulb globe temperature (WBGT) index to evaluate the risk of heat stroke in daily life. According to this guideline, WBGT = 25 °C or higher is defined as a criterion for heat stroke risk in activities of moderate or higher intensity, and WBGT = 28 °C or higher is defined as a criterion for heat stroke risk in all activities. ASHRAE Fundamentals [78] also indicates ET* = 35 °C as a general standard of concern for heat stroke in hot environments. Conversely, Public Health England [79] summarizes the effects of low-temperature environments on health. According to the guidelines given by Public Health England, indoor temperatures below 18 °C may increase the risk of increased blood pressure and cardiovascular diseases, and indoor temperatures below 16 °C may reduce resistance to respiratory diseases. In addition, Collins et al. [80] reported that indoor air temperatures below 15 °C increased the burden on the cardiovascular system in the elderly.

Based on these findings, we treat 25 °C (WBGT), 28 °C (WBGT), and 35 °C (ET*) as the warning lines for heat stroke risk, and 18 °C (t_a), 16 °C (t_a), and 15 °C (t_a) as the warning lines for cardiovascular and respiratory disease risk in cold environments in this study.

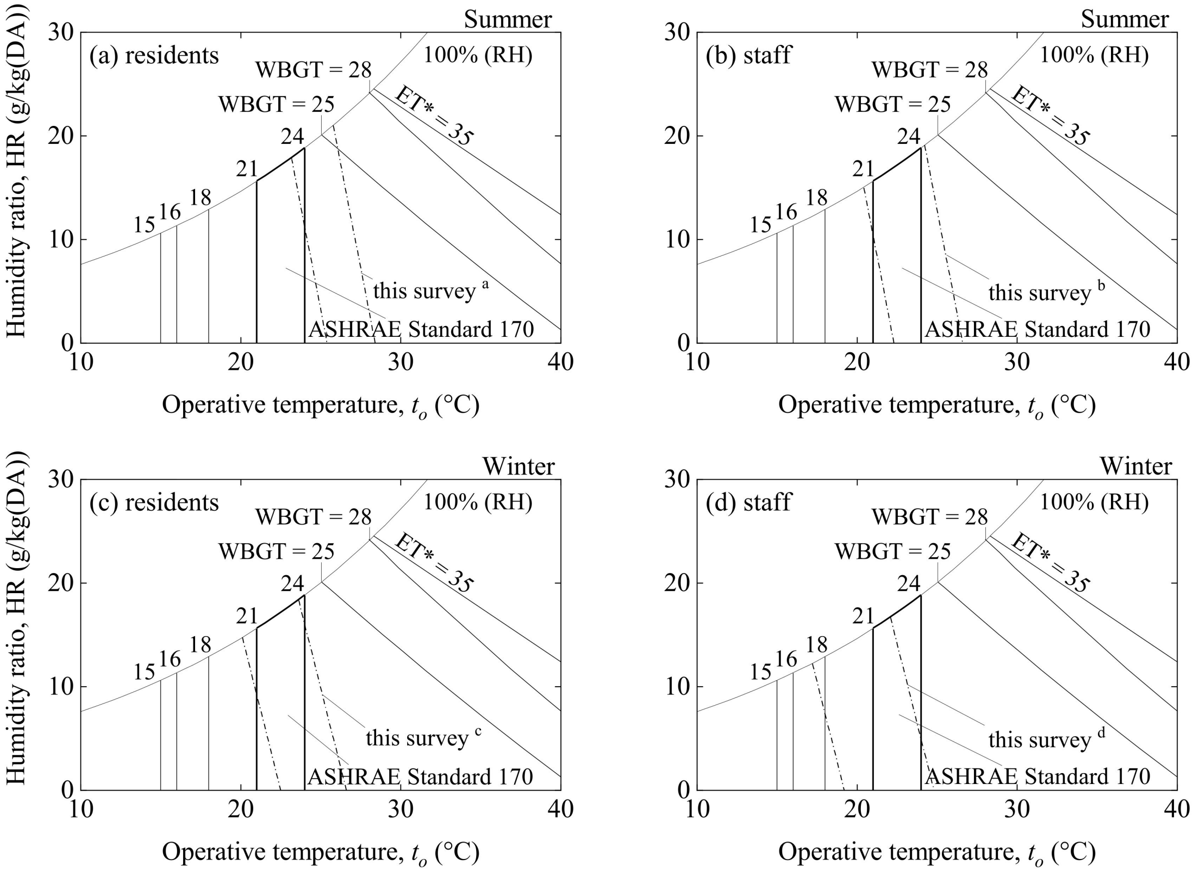


Figure 18. Comparison of the warning line for health risk with the subjects' 80% thermal acceptability limits and the indoor temperature range recommended by ASHRAE Standard 170: (**a**) residents and (**b**) staff in summer and (**c**) residents and (**d**) staff in winter. Remarks: [a] 80% acceptability limit for residents in summer, shown in Figure 16a. [b] 80% acceptability limit for staff in summer, shown in Figure 16b. [c] 80% acceptability limit for residents in winter, shown in Figure 16c. [d] 80% acceptability limit for staff in winter, shown in Figure 16d.

In Figure 18a, it was confirmed that the upper limit of the 80% acceptability limit for residents in summer (t_o = 28.4 °C) exceeded the three heat stroke warning lines of 25 °C (WBGT), 28 °C (WBGT), and 35 °C (ET*) in a high humidity environment. In addition, Figure 18d confirms that the lower limit of the 80% acceptability limit for staff in winter exceeds the alert line for cardiovascular disease risk of 18 °C (t_a). These results confirmed that meeting the thermal comfort requirements of occupants is not equivalent to meeting their physical health requirements. Therefore, it is necessary to consider a reasonable temperature range for both occupant thermal comfort and health.

ASHRAE Standard 170 [62,76] summarizes the minimum requirements for the indoor thermal environment, including RH and indoor temperature, in addition to ventilation requirements in health care institutions, including hospital spaces, outpatient spaces, and nursing home spaces. The standard specified recommended temperature range for indoor spaces in nursing homes is 21–24 °C for the 2017 standard and 21–29 °C for the 2021 standard. The temperature range of the 2017 standard met all the criteria for health risks for the low and high-temperature sides, as shown in Figure 18. In contrast, the 2021 standard, which extends the upper limit of the temperature range by 5 °C, may exceed the three heat stroke warning lines of 25 °C (WBGT), 28 °C (WBGT), and 35 °C (ET*) in high humidity environments. In addition, as shown in Figure 18a–d, the temperature range of 21–24 °C includes 80% acceptability limits by the comfort zone. Therefore, the 2017 standard can meet the thermal comfort of occupants.

The World Health Organization [81] defines a range of 18 to 24 °C as the minimum indoor temperature necessary to maintain good health. However, for vulnerable groups, such as the elderly, children, and people with chronic diseases (especially cardiopulmonary diseases), it recommends a minimum indoor temperature higher than 18 °C. Bills [68] studied thermal comfort and health risks in 18 elderly households in South Australia. He reported an increase in symptoms such as cough, headache, and joint pain in senior citizens during cold and warm months and reported that the range of indoor operative temperatures with the fewest health symptoms ranged from 21.0 to 24.3 °C. Based on this information, we concluded that the recommended temperature range for indoor spaces in nursing homes in terms of health risks and thermal comfort is 21–24 °C, as indicated in ASHRAE Standard 170-2017 [76].

3.7. Future Forecasts of Total Heat Loads

There are two types of heating and cooling setpoints to be set in the simulation of heat load in this study. The first considers the temperature range based on the measured data of this study. The second considers the temperature range that considers the improvement of the thermal comfort of occupants and the control of health risks. The indoor operative temperature at the time of the subject's voting of this study was 16.6–26.7 °C in winter and 20.1–27.6 °C in summer. Except for 0.2% of the measurements in winter, the indoor operative temperature was controlled within the range of 17 to 28 °C throughout the year. Therefore, 17 °C and 28 °C are set as the first heating and cooling setpoints. The analysis in Section 3.6 confirms that even if the thermal environment meets the thermal comfort of occupants, the physical health risk of occupants may be a concern. In this study, the recommended indoor temperature range for the indoor space of a nursing home is considered to be 21–24 °C, considering the control of health risks of the elderly. Therefore, 21 °C and 24 °C are set as the second heating and cooling setpoints.

Figure 19 shows the future forecasts of the total annual heat load in the common space, where (a) the setpoint temperature of 17–28 °C and (b) the setpoint temperature of 21–24 °C result from the analysis under RCP 2.6, and (c) the setpoint temperature of 17–28 °C and (d) setpoint temperature 21–24 °C result from the analysis under the conditions of RCP 8.5. A common prediction of the energy performance of buildings in future weather scenarios is that a paradigm shift will occur owing to a decrease in heating load and an increase in cooling load, resulting in an overall increase in total energy consumption for heating and cooling [36]. However, it is noteworthy that in the results of this study, the total heat loads did not change significantly over the period 2020–2050 and between the two future scenarios. The total estimated heat load in 2050 decreased by 3.4% and 4.5% in Figure 19a,c, respectively, and increased by 0.6% and 2.1% in Figure 19b,d, respectively, compared to the total heat load in 2020. The difference in total heat load between the different temperature settings is clear. The total annual heat load for the conditions with a setpoint of 21–24 °C was on average 120.2% higher than for the conditions with a setpoint of 17–28 °C. Comparing the window conditions, the condition with the lowest U-value and SHGC of windows reduced the total heat load the most. Conversely, the condition with the highest window U-value and the heat shield film applied had the highest total heat load.

3.8. Future Forecasts of Heating Loads

The future forecasts of the annual heating load in the shared space are shown in Figure 20, where (a) the setpoint temperature of 17–28 °C and (b) the setpoint temperature of 21–24 °C result from the analysis under RCP 2.6, and (c) the setpoint temperature of 17–28 °C and (d) the setpoint temperature of 21–24 °C result from the analysis under RCP 8.5. In Figure 20, the heating load shows a decreasing trend from 2020 to 2050. The heating load under the 2050 condition decreased by 12.7% on average compared to the heating load under the 2020 condition. It can also be observed that between the two future scenarios, the heating load under the RCP 8.5 condition is more variable than that under the RCP 2.6 condition. The conditions with a setpoint temperature of 21–24 °C resulted in an average increase of 78.3% in the annual heating load compared to the conditions with a setpoint temperature of 17–28 °C. The lowering of the SHGC of windows showed a tendency to increase the heating load. The condition with moderate *U*-value and SHGC of windows reduced the heating load the most. Conversely, the condition with the highest window *U*-value and the heat shield film applied had the highest heating load.

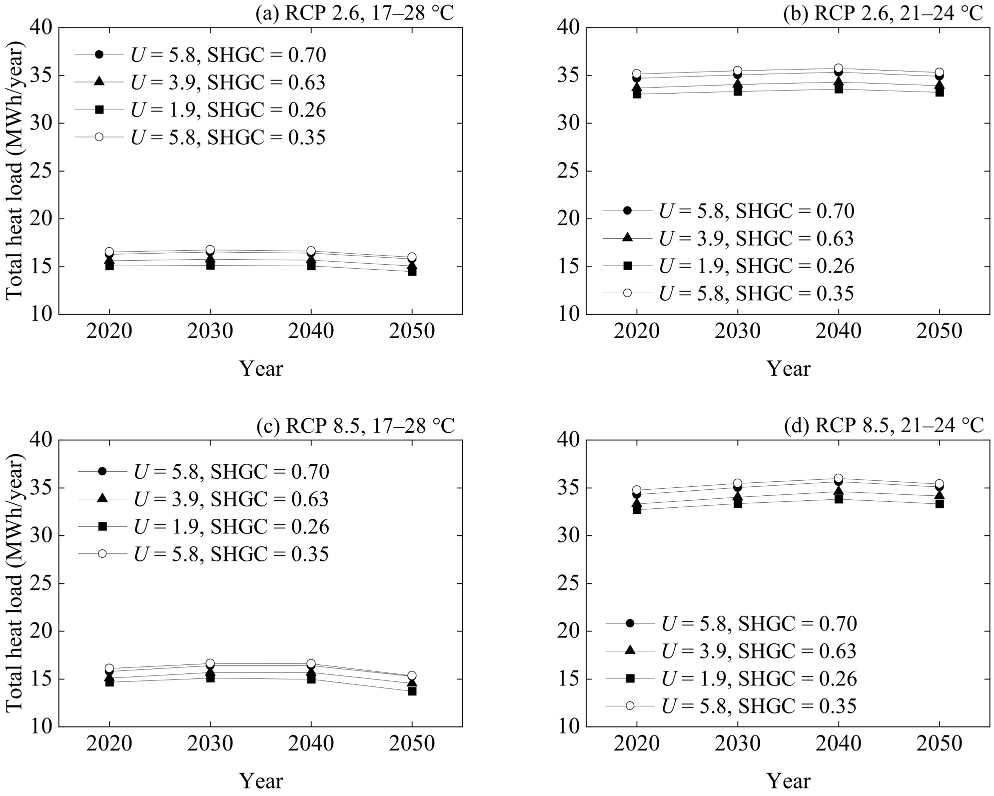


Figure 19. Annual total heat loads for common spaces in each scenario: (**a**) the setpoint temperature of 17–28 °C and (**b**) the setpoint temperature of 21–24 °C result from the analysis under RCP 2.6, and (**c**) the setpoint temperature of 17–28 °C and (**d**) the setpoint temperature of 21–24 °C result from the analysis under RCP 8.5.

3.9. Future Forecasts of Cooling Loads

The future forecasts of the annual cooling load in the shared space are shown in Figure 21, where (a) the setpoint temperature of 17–28 °C and (b) the setpoint temperature of 21–24 °C result from the analysis under RCP 2.6, and (c) the setpoint temperature of 17–28 °C and (d) the setpoint temperature of 21–24 °C result from the analysis under RCP 8.5. In Figure 21, the cooling load shows an increasing trend from 2020 to 2040. In addition, the cooling load in 2050 shows a decreasing trend except for the condition of RCP 8.5 and setpoint temperature of 21–24 °C shown in Figure 20d. The cooling load in 2050 increased by 26.5% on average compared to the cooling load in 2020. Conditions with a setpoint temperature of 21–24 °C increased the annual cooling load by 231.4% on average compared to conditions with a setpoint temperature of 17–28 °C. The lowering of the SHGC of windows showed a tendency to reduce the cooling load. The condition with the lowest *U*-value and SHGC of windows reduced the cooling load the most. Conversely, the condition with the highest window *U*-value and no heat shield film had the highest cooling load.

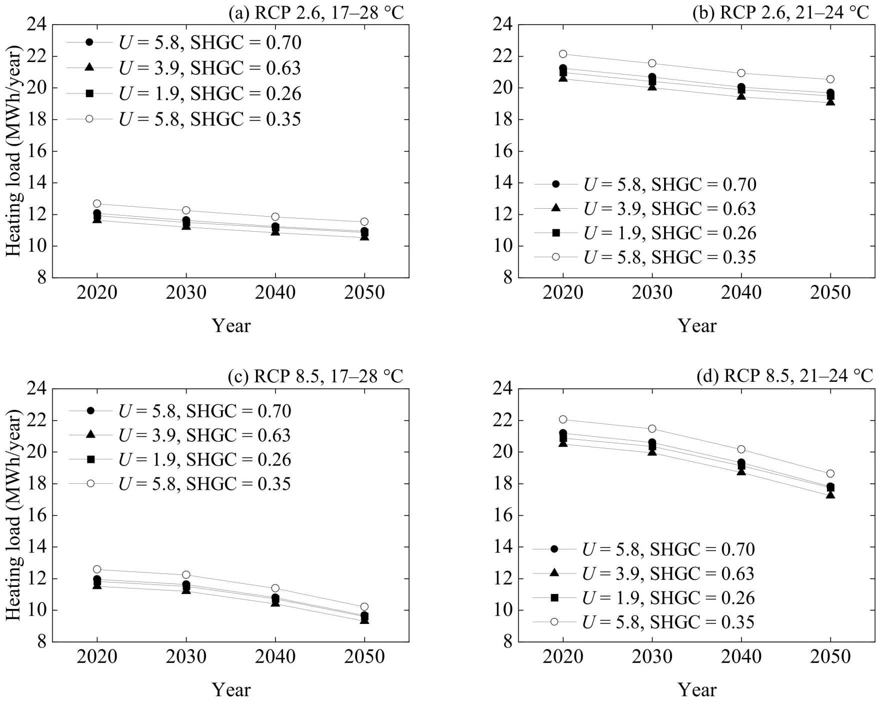


Figure 20. Annual heating loads for common spaces in each scenario: (**a**) the setpoint temperature of 17–28 °C and (**b**) the setpoint temperature of 21–24 °C result from the analysis under RCP 2.6, and (**c**) the setpoint temperature of 17–28 °C and (**d**) the setpoint temperature of 21–24 °C result from the analysis under RCP 8.5.

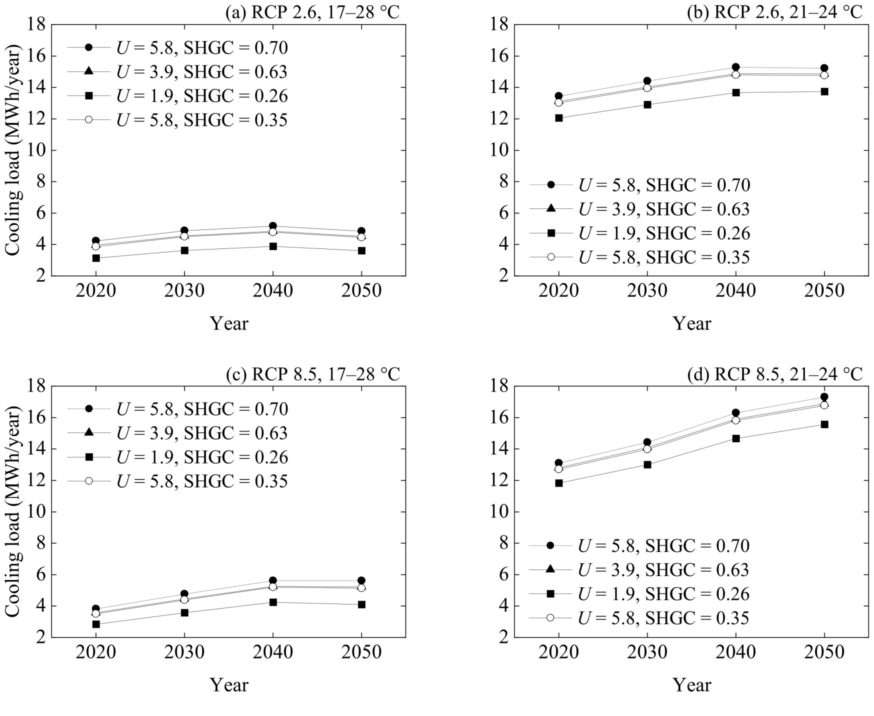


Figure 21. Annual cooling loads for common spaces in each scenario: (**a**) the setpoint temperature of 17–28 °C and (**b**) the setpoint temperature of 21–24 °C result from the analysis under RCP 2.6, and (**c**) the setpoint temperature of 17–28 °C and (**d**) the setpoint temperature of 21–24 °C result from the analysis under RCP 8.5.

4. Conclusions

An investigation of thermal comfort and a building energy simulation was conducted in an air-conditioned nursing home in Nagano, Japan. The field survey was conducted between June 2020 and June 2021. In this study, the thermal sensation of the residents and staff and the expected thermal sensation of residents were investigated. In addition, regression analysis of the indoor operative temperature and the thermal sensation was used to calculate the neutral temperature and the acceptable range, and the difference in the thermal comfort of the occupants and staff was analyzed. In addition, future weather data for the period 2020–2050 was used to analyze the annual heating and cooling loads in the common spaces. Comparing four different window conditions, the reduction in heating and cooling loads owing to differences in window heat transmittance and solar heat gain were examined. The results of this study will serve as a useful reference for a wide range of stakeholders, including managers or designers of nursing homes. The results and limitations of this study, as well as future work, are presented below.

The mean value of the indoor operative temperature was 24.8 °C in summer and 21.7 °C in winter. The indoor operative temperature of the common space at the time of the subject's voting was controlled within the range of 17 to 28 °C throughout the year. The mean values of outdoor air temperature were 20.5 °C in summer and 4.2 °C in winter. Furthermore, the mean values of the running mean outdoor temperature were 16.5 °C in summer and 4.2 °C in winter. The thermal sensation survey confirmed that both residents and staff had little thermal dissatisfaction with the indoor thermal environment of the common space. It was confirmed that the residents' TSV and TSV_i or the staff's TSV and TSV_i had statistically different distributions. Although the staff answered the TSV_i with the expectation that her own thermal sensation and the thermal sensation of residents was different, it may be difficult to accurately predict the thermal sensation of residents. In this study, linear regression was used to calculate the neutral temperature and acceptable range of residents and staff. In the summer survey, the neutral temperature of the residents was 25.9 °C, and the neutral temperature of the staff was not estimated because it was extrapolated. For the winter survey, the neutral temperature for residents was 23.8 °C and for staff was 23.8 °C. Acceptable ranges for residents and staff were not estimated because they were extrapolated. The neutral temperature of the residents predicted by the PMV was 25.2 °C in summer and 23.7 °C in winter. The neutral temperature of the staff as predicted using PMV was 22.7 °C in summer and 21.2 °C in winter. PMV could predict the thermal neutrality of residents in this study; however, the sensitivity of warm and cold to the operative temperature differed from the TSV of residents. In contrast, PMV predicted the thermal neutrality of the staff in this study to be on the high-temperature side in summer and on the low-temperature side in winter, although the sensitivity of the thermal sensation to the operative temperature was similar to the TSV of the staff.

In this study, participants were not selected based on pre-existing medical conditions or illnesses to understand the current status of thermal sensation and thermal perception of elderly people living in the study facilities. Therefore, it should be noted that the analysis of thermal comfort may include bias owing to the responses of subjects with poor cognitive function. In the future, it is desirable to analyze the relationship between pre-existing medical conditions and the thermal comfort of subjects. In addition, only one staff member participated in this study; thus, the number of subjects was insufficient to analyze the thermal comfort and to consider individual differences among the subjects. Additional analysis with many staff subjects is necessary to increase the reliability of the findings of this study.

After summarizing the findings related to health risks in indoor thermal environments in this report, we concluded that the recommended temperature range for indoor spaces in nursing homes is 21–24 °C, as recommended in ASHRAE Standard 170-2017. A comparison of the 80% acceptability limit of the residents calculated using the analytical comfort zone method with the health risk criteria confirmed the possibility of exceeding the heat-stroke warning line in hot and humid environments. It was also confirmed that the lower limit of the 80% acceptability limit for staff in winter was above the warning line for risk of cardiovascular diseases. It is important for air conditioning management to consider health risks in addition to thermal comfort.

It is confirmed that the annual total heat load in 2050 will not change significantly compared to the total heat load in 2020. Therefore, the increase in cooling load is compensated by the decrease in heating load. The heating load increased by an average of 78.3% and the cooling load increased by an average of 231.4% for a setpoint of 21–24 °C compared to the setpoint of 17–28 °C, resulting in an average increase in total heat load of 120.2%. Comparing the window conditions, the condition with the lowest *U*-value and SHGC reduced the total annual heat load the most. The lowering of the solar heat gain coefficient of windows was beneficial to reduce the cooling load. Conversely, the raising it was beneficial to reduce the heating load. Therefore, to effectively reduce the total annual heat load, it is necessary to change the solar radiation shielding of windows between the cooling and heating periods.

The nursing home under study has a multi-story car park located on its south side, which may have a certain effect on the amount of solar heat gain of the building. However, the building simulations in this study did not consider the effect of solar heat gain owing to three-dimensional shielding.

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