Evaluation on present situations of safety on thermal environment in residential houses in Japanese winter season using BEST-H program

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Abstract. In this paper, the present situations on the safety of thermal environment in residential houses in winter season were evaluated by using the BEST-H program, a computation tool for analysing the thermal load in residential houses. In this analysis, the climate conditions for each primary division area in Japan were imposed to the input conditions for the thermal load computations. We also evaluated the safety of thermal environment with the hazard rate for both the cardiac and the brain diseases from the combination between the computational results using the BEST-H program and the several statistical data. Through the investigations, the following two findings were obtained: (1) the proposed method was validated for the evaluation of the safety on the thermal environment in the residential houses in winter season by comparing the computational results with the statistical data from the Population Survey Report in Japan.: (2) More houses with suitable insulation performance should be established in the western area and northern part of the Kanto area in Japan. The near future direction of our study is to evaluate variable countermeasures, such as one-room insulation.

1 Introduction

The elderly population in Japan has steadily increased in recent years. The rate of the elderly aged 75 or over is predicted to reach approximately 25% of the entire population of Japan in 2025 [1, 2]. Thus, the relationship between the indoor environment in residential houses and the health of residents becomes an attractive study topic. In particular, the cold environment in rooms in the winter season is considered to be related to respiratory and cardiovascular diseases. In the winter, the cold environment in residential houses has a strong correlation with insulation performance. The majority of residential houses in Japan do not meet the acceptable performance level outlined in current standards for the building energy efficiency act by the Ministry of Land, Infrastructure, Transport and Tourism in Japan (MILT). Hence, various researchers inside and outside Japan have conducted studies concerning the abovementioned issues using both field observations and questionnaire surveys [3-6].

The computational method based on the network model for heat and ventilation in a building (NMHVB) has gained attention as an effective tool for investigating the relationship between house insulation performance and resident's health. This tool was originally developed for the evaluations of annual variations of both room temperatures and air-conditioning loads; therefore, it enables the evaluation of several countermeasures on the energy savings in a building. Additionally, the annual variations in air temperature in rooms are expected to enable the evaluation of both the present state and the effects of installing insulation in indoor spaces on the thermal comfort [7]. In a previous study, we proposed an evaluation method based on numerical analysis using the building energy simulation tool for houses (BEST-H) program [8]. We also applied it to propose indexes for the evaluation of hazards, such as the heat shock degree hour [9,10]. The proposed method was not validated in previous studies owing to a lack of statistical or measurement data. However, as previously mentioned, recent studies have introduced useful data to the validation of our computational method. In particular, Umishio et al. [6] examined the relationship between the thermal environment and the health of Japanese residents and proposed an estimate equation for blood pressure (BP) at wake-up time for residents based on multi-regression analysis.

In the present study, a computational method for the BP at the wake-up time is proposed by imposing the results of the heat and ventilation network analysis on Umishio's equation mentioned above. This tool was applied to the evaluation of the thermal environment in a residential house during the winter season. Additionally, an estimation method for the hazard rate (HR) from the BP for both stroke mortality and ischemic heart disease (IHD) is proposed. Moreover, the application study of evaluations of the present state and the improvement capability of the thermal environment in each prefecture in Japan is introduced.

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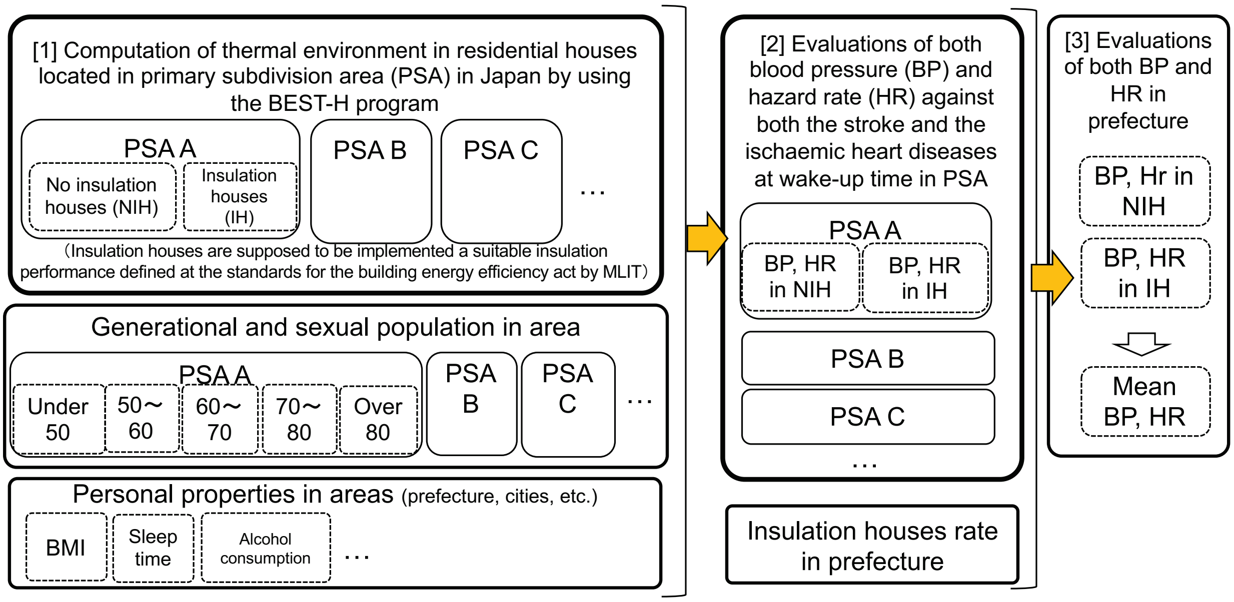


Fig. 1. Flowchart of evaluation on annual variations of both the thermal environment and the safety against cold in a residential house.

2 Methods

2.1 Flow of the evaluation method

Figure 1 outlines the computational method for evaluating both the thermal environment and the safety of residents at wake-up time during the winter season. The present method is composed of the following three steps: (1) Computation of the thermal environment in residential houses located in primary subdivision areas (PSAs) in Japan using BEST-H program; (2) Evaluation of BP and HR against stroke and IHD at wake-up time in each PSA; and (3) Evaluation of BP and HR in each prefecture.

2.2 Outline of the BEST-H program

BEST-H program is a NMHVB and has been developed by the Institute for Built Environment and Carbon Neutral for SDGs (IBECs) [8]. Figure 2 summarizes the primary flow of the analysis procedure of this program. At the first step of the computations, the following data are used as the computational conditions: (1) meteorological conditions; (2) room allocation in a house; (3) variations of both walls and windows; and (4) schedules concerning the time spent in rooms or the equipment use. BEST-H program outputs the annual variations of the following results every 5 min: (1) meteorological conditions, (2) indoor thermal environments, and (3) energy consumption.

2.3 Estimation of blood pressure at wake-up time

The daily BP at wake-up time in residential houses is estimated using a regression expression proposed by Umishio et al. [6] based on multivariable analysis. This expression considers the following nine arguments: (1) air temperatures in both living room and bedroom, (2)

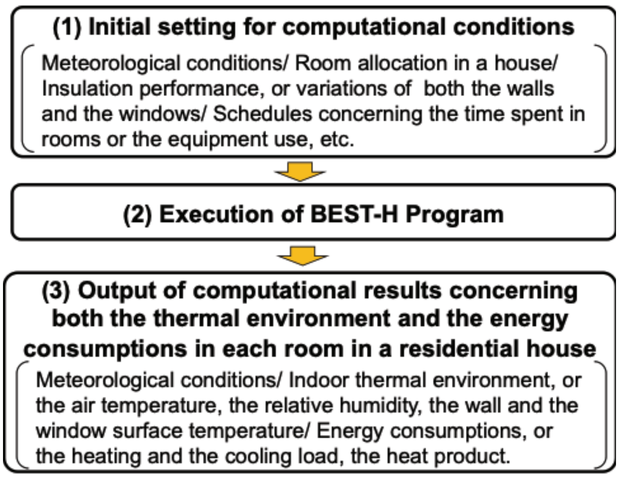


Fig. 2. Flow chart of computations by BEST-H Program.

sleeping environment (hours and quality), (3) alcohol consumption habits, (4) gender, (5) body mass index, (6) fitness habits, (7) dietary habits, (8) smoking habits, and (9) outdoor air temperature. The proposed method enables the evaluation of the BP separated by insulation performance of house, gender, and age group. In the present analysis, we estimated the morning BP in each residential house for each PSA from the results of the BEST-H analysis and the statistical dataset such as population composition, personal properties shown in Fig. 1.

2.4 Evaluation of hazards against stroke and ischemic heart diseases

The BP at wake-up time is the primary factor related to safety of the thermal environment in the winter season for inhabitants in a residential house. However, other indexes are necessary, because the BP does not directly express the risk of stroke and IHD. In this study, we applied the HR as a practical index against those diseases. The HR was derived from the data analyses in many different locations in the world [11]. Figure 3

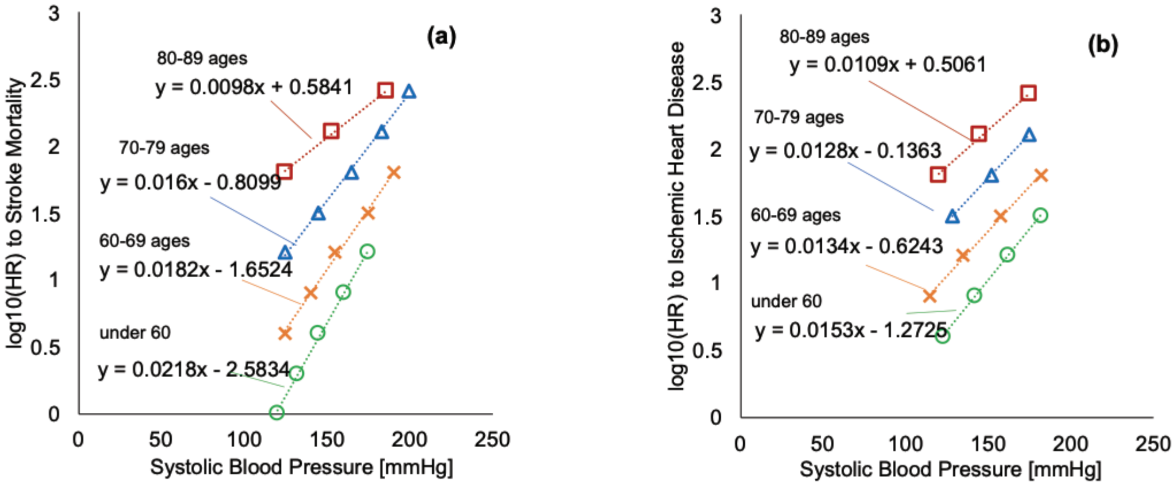


Fig. 3. Relationships between the systolic BP and the HRs to both the stroke mortality (SM) and the ischemic heart disease (IHD) rates in each decade of age. (a) Relationship to SM, (b) Relationship to IHD.

illustrates the relationship between the BP and the HRs for both the stroke mortality and the IHD rates for different ages. The vertical axis in this figure indicates the common logarithms (LOG10) of the HR. The value 0 in the vertical axis is equivalent to the hazard level for healthy subjects under the age of 60, whereas the values of 1 to 10 times stronger than them. In the present analysis, we derived it from the results of the morning BP estimated by the method described at previous section to evaluate the safety of the thermal environment.

2.5 Evaluation of hazards in each prefecture

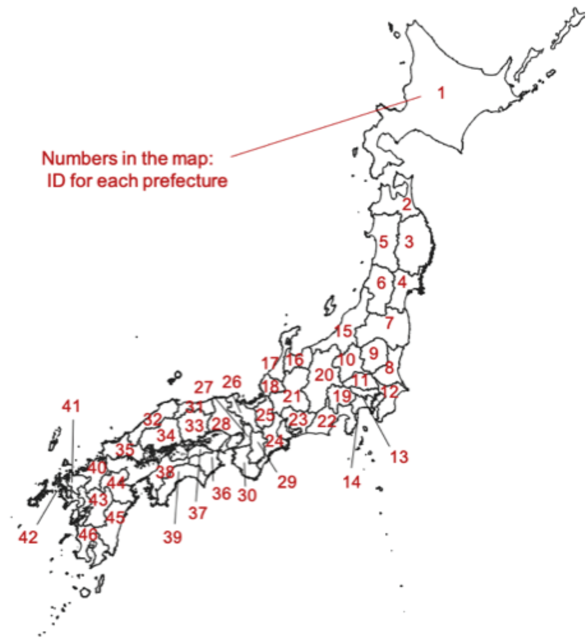
We can examine the annual variations of HR for each gender, generation, and type of house. From the dataset of these HRs, we examine annual variations of the mean HR weighted with both the composition of the population and the rate of residential houses with suitable insulation in each prefecture.

3 Outline of analysis

3.1 Study Area

The study area in the present analysis covers all Japanese prefectures except for Okinawa, where heating periods are not required. In this analysis, we examined the thermal environment in residential houses established in the PSAs in each prefecture. A PSA is determined in each prefecture by considering the following characteristics: local climate, disasters, and geography. Figure 4 illustrates the locations of the prefectures in the study area. The numbers in parentheses in the table indicate the numbers of the PSA in each prefecture. The entire study area in the present analysis contains 135 PSAs.

Figure 5 illustrates the plan of a residential house, named a "self-sustainable circulation house model," or a timbered house [13], for the BEST-H analysis. In each PSA, the insulation performances of two types of residential houses were examined under the climate conditions. Type1 house has a low insulation level without implementing insulation materials and windows,



No.	Name	No.	Name	No.	Name
1	Hokkaido (16)	17	Ishikawa (2)	33	Okayama (2)
2	Aomori (2)	18	Fukui (2)	34	Hiroshima (2)
3	Iwate (3)	19	Yamanashi (2)	35	Yamaguchi (4)
4	Miyagi (2)	20	Nagano (3)	36	Tokushima (2)
5	Akita (2)	21	Gifu (2)	37	Kagawa (1)
6	Yamagata (4)	22	Shizuoka (4)	38	Ehime (3)
7	Fukushima (3)	23	Aichi (2)	39	Kochi (3)
8	Ibaragi (2)	24	Mie (2)	40	Fukuoka (4)
9	Tochigi (2)	25	Shiga (2)	41	Saga (2)
10	Gunma (2)	26	Kyoto (2)	42	Nagasaki (4)
11	Saitama (3)	27	Osaka (1)	43	Kumamoto (4)
12	Chiba (3)	28	Hyogo (2)	44	Oita (4)
13	Tokyo (4)	29	Nara (2)	45	Miyazaki (4)
14	Kanagawa (2)	30	Wakayama (2)	46	Kagoshima (4)
15	Niigata (4)	31	Tottori (2)	Numbers in parentheses: Numbers of PSA in each prefecture	
16	Toyama (2)	32	Shimane (3)		

Fig. 4. Study area and ID for each prefecture.

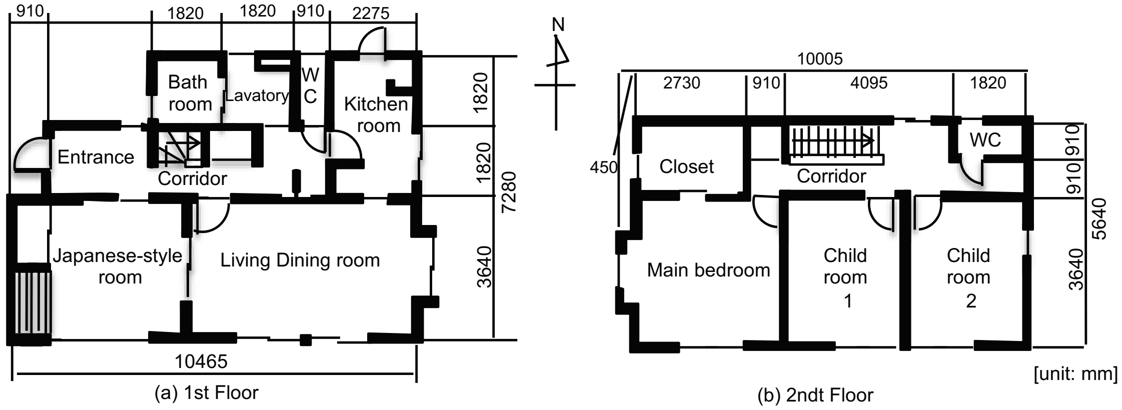
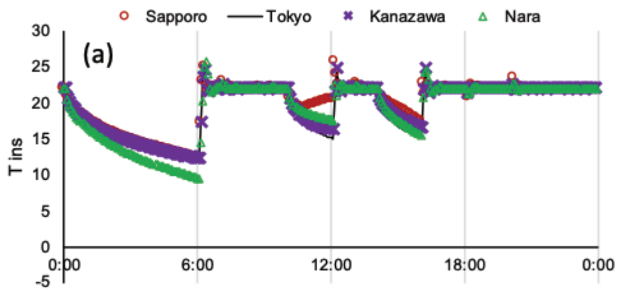
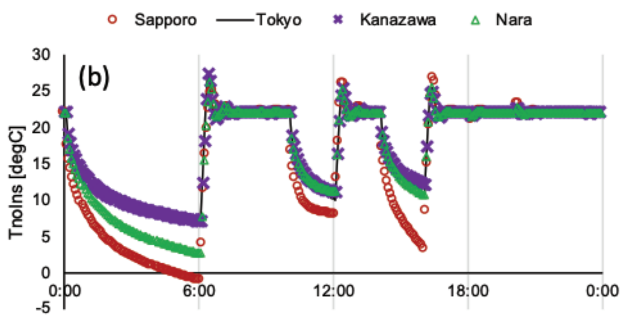


Fig. 5. Plan of the residential house for the BEST-H analysis.

Table 1. Coefficients of both U values and heat gain rate of for each type of residential house

No	Regional level	Mean U value in each part W/m²K					Heat gain rate by solar radiation for opening at daytime
		Ceiling	Exterior wall	Floor	Opening at daytime	Opening at night time	
N	Non-insulation	3.06	2.30	3.36	5.42	4.23	0.47
V , VI	Kyushu, Shikoku, Kinki, Tokai, southern part of Kanto	0.24	0.53	0.48	3.63	3.30	0.66
IV	Hokuriku, Shin-etsu, Northern part of Kanto, Southern part of Tohoku	0.21	0.46	0.41	3.39	2.67	0.53
III	Hill district in main island, Northern part of Tohoku	0.15	0.34	0.31	2.38	1.79	0.53
II	South-West part of Hokkaido	0.13	0.28	0.25	1.88	1.49	0.52
I	Other part of Hokkaido	0.09	0.21	0.19	1.32	1.11	0.41





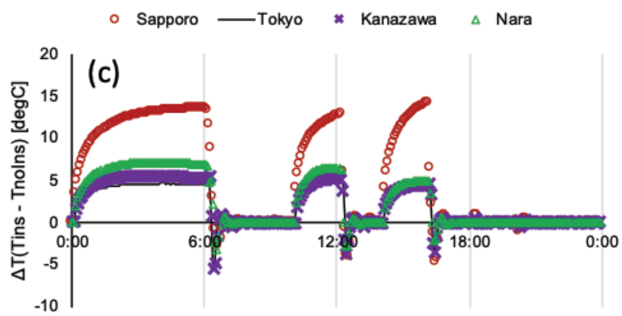


Fig. 6. Diurnal variations of air temperature in LD on typical cold day in the winter season (Feb. 02). (a) Houses for the suitable insulation performance (Tins), (b) Houses for the low insulation performance (TnoIns), (c) Difference between with and without insulation (Tins – TnoIns).

whereas type2 house has a suitable insulation level required as per the standards for the building energy efficiency act by MILT [14]. Table 1 summarizes the coefficients of overall heat transmission, or UA value, and rates of heat gain by solar radiation for each regional insulation level required in the standards. The values for the non-insulation (N) houses and those over the V insulation level (V, VI) houses were set in accordance to Serikawa et al. [7]. The values for levels under the IV insulation level (I, II, III, IV) were also estimated by multiplying each value with the rate of UA value for residential houses in the target region to that in the region V. For example, the UA value in region IV is defined as 0.75 W/(m²K), whereas that in region V is 0.87. Hence, the UA value for each part is obtained by multiplying by 0.86 (=0.76/0.87).

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3.2 Meteorological conditions

In the present analysis, data for the standard year of the Expanded Automated Meteorological Data Acquisition System (AMeDAS) were applied to the meteorological Data for the BEST-H program. The start of the analysis period was set to be 0:00 on December 16^{th} in last year for the target year, in order to reduce the effects of initial conditions of the calculation.

4 Results and discussions

4.1 Diurnal variations of air temperature on the coldest day

Figure 6 illustrates the variations of the air temperature in Living Dining (LD) room on February 2^{nd}, or a typical cold day in the winter season. In this figure, the results of the following four cities are shown with a space constraint: Sapporo (North city, high insulation performance house), Tokyo (Mid coastal city facing Pacific Ocean, low insulation performance house, national capital of Japan), Kanazawa (Mid coastal city facing Japan Sea, low insulation performance house, heavy snow in the winter season), Nara (Mid inland city, low insulation performance house). The results for the houses with suitable insulation performance are shown in Fig. 6(a), whereas those for houses with low insulation houses are shown in Fig. 6(b). Figure 6(c) shows the variations of the differences between the houses with and without insulation. For both situations, in the heating period, the air temperature was approximately 22 °C, and rapidly decreased when the heating systems did not work. In the results for the low-insulation houses, the values at wake-up time for Sapporo, Tokyo, Kanazawa, and Nara were approximately -1 °C, 7.5 °C, 7.0 °C, and 2.6 °C, respectively. The values of Sapporo were considerably low due to the cold climate conditions, but increased after installing the insulation; the difference with and without insulation reached approximately 13.5 °C at wake-up time. In contrast, the value for the Nara house with insulation was approximately 9.4 °C, which is considerably low when compared to that of other cities. This is due to radiative cooling, resulting in a large amount of heat near the ground to return to the clear sky on Nara.

4.2 HR Distributions

Figure 7 shows the HR distributions for each prefecture in both the heating period and the mid-period between heating and cooling periods. The distributions of rates of insulation houses (RI) in each prefecture are also shown. The RI values were estimated with reference to Ikaga et al. [5]. The HR values in the mid period ranged

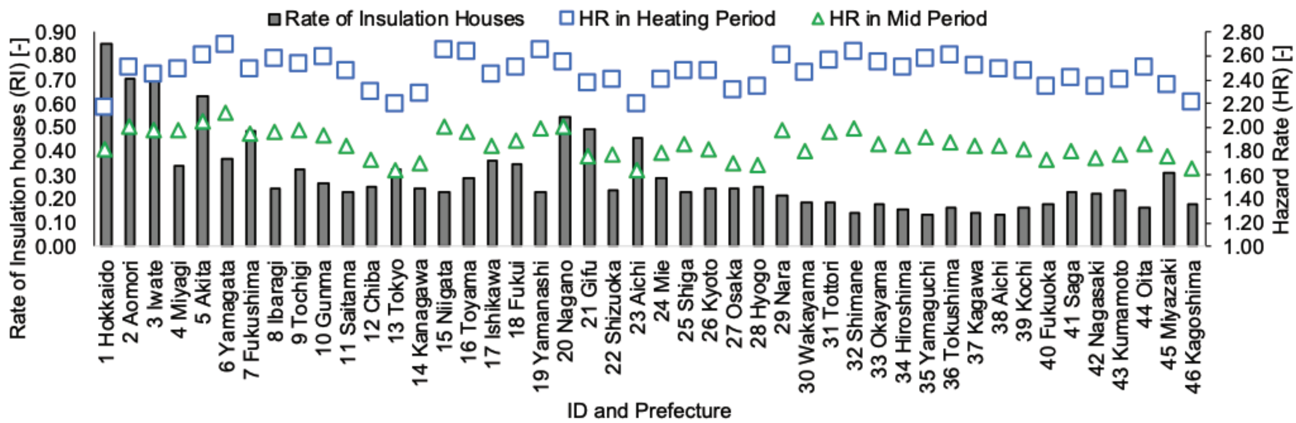

Fig. 7 Distributions of HR for each prefecture in both the heating period and the mid period between heating and cooling periods.

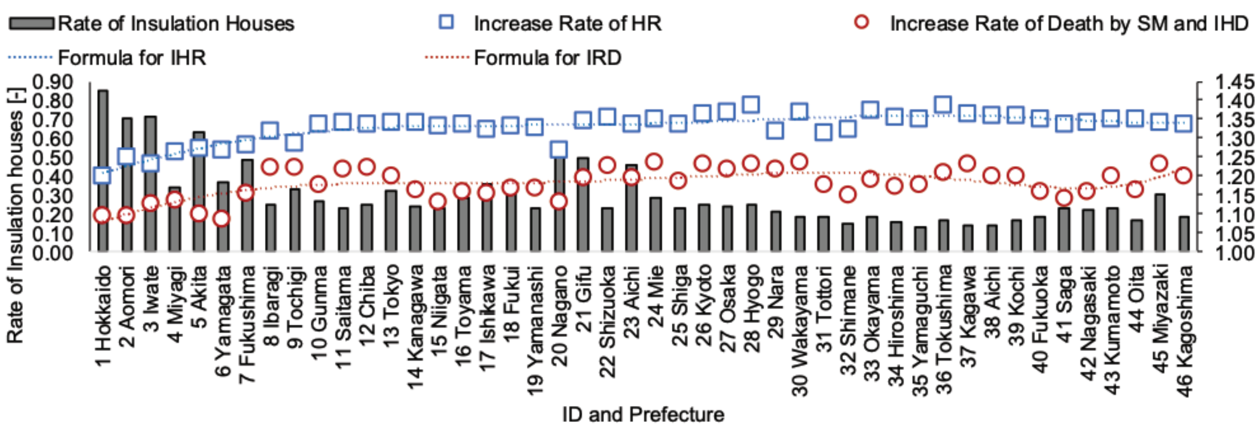

Fig. 8. Distributions of increase rate of both HR (IHR) and Death (IRD) by seasonal change from the mid to the heating periods in each prefecture.

from approximately 1.64 to 2.12, whereas those in the heating period ranged from approximately 2.17 to 2.69. Hence, the HR values in the heating period were larger than those in the mid period.

Figure 8 depicts the seasonal distributions of the increase rate of HR (IHR) from mid- to heating periods in each prefecture. The statistical data on the increase rate of death (IRD) by both stroke and IHDs are also shown. The data were estimated from the Japanese Population Survey Report from 2015 to 2019 [15]. The IHR and IRD values ranged from approximately 1.29 to 1.39 and 1.08 to 1.24, respectively.

4.3 Validity of computational results

Figure 9 illustrates the relationship between the RI and IHR values. From the results, the IR moderately correlates with the IHR because the value of the coefficient of determination, R^2, is approximately 0.67. Figure 10 shows the relationship between the IHR and IRD values. In this figure, both the vertical and the horizontal axes are defined by the values of the common logarithms (LOG10) for the IHR or IRD. The R^2 value for the approximation equation is approximately 0.51. Hence, the IHR moderately correlates with the IRD. From these investigations, the validity of the computational method in the present analysis was verified.

4.4 Effects of insulation on HR

From Fig. 11, we evaluate the effects of insulation on the HR values. The vertical and horizontal axes in this figure represent HR values for non-insulation and suitable insulation houses, respectively. The red and green circle marks show the results for the heating and mid-periods, respectively. These values are calculated under the relationship between the insulation performances of each type of residential house, the meteorological conditions, and population compositions in each PSA. The values of IHRs shown in Fig. 9 were also derived by averaging the IHR (red marked value / blue marked value) weighted with the RI. From the approximate expression, the HR value for non-insulation houses is approximately 1.25 times larger than that for suitable insulation houses. In particular, this tendency is quite remarkable for Hokkaido, where the HR value for non-insulation houses is 1.4 times larger than that for suitable insulation houses. This is caused by the facts that insulation houses in Hokkaido have adequate performance against cold climate conditions compared to houses in other prefectures. According to the findings, an increase in the number of suitable insulation houses reduces the risk of death from both stroke and IHD.

4.5 Effects of increase of insulation houses on improvement of HR

From the examination described in the previous section, an increase in suitable insulation houses is expected because these houses result in an evident improvement

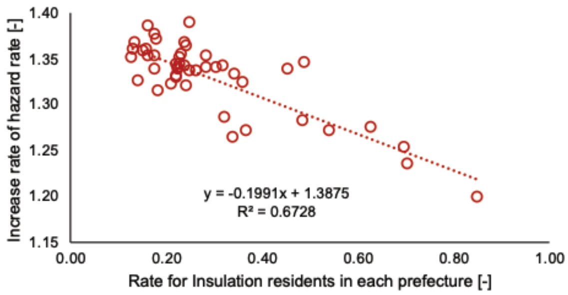

Fig. 9. Relationship between the values of Rate for Insulation Residents (RI) and those of Increase Rate of Hazard Rate (IHR).

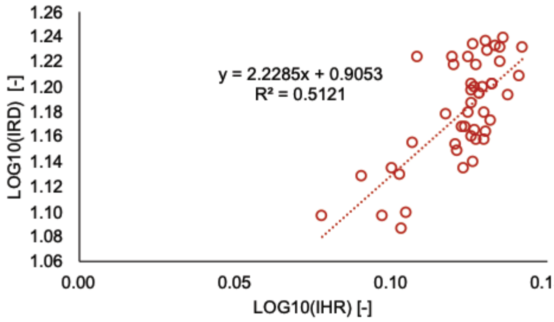

Fig. 10. Relationship between the values of Increase Rate for Hazard Rate (IHR) and those of Increase Rate of Death (IRD).

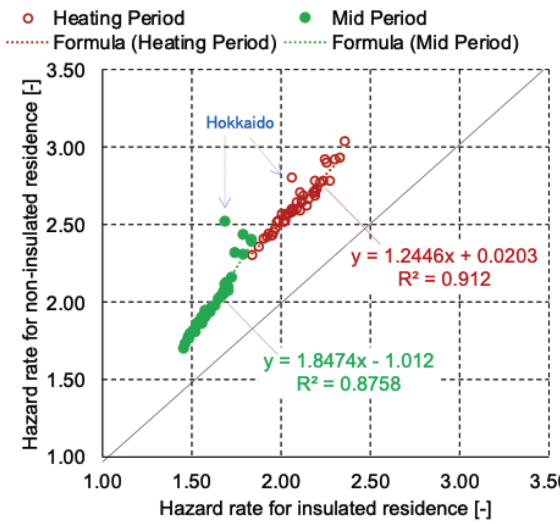

Fig. 11. Relationship between HRs of both the no-insulation residential houses and the suitable insulation residential houses.

in the safety of the thermal environment in indoor spaces. However, the present rate of insulation houses is different in each prefecture. As a result, the potential for mitigating hazards during the winter season varies by prefecture. In this section, we attempt to evaluate this improvement potential by comparing the HR values in the heating period for the present state with those for an idealized case in which all residential houses have suitable insulation performance. Figure 12 illustrates the distributions of HR values in the heating period for each prefecture. In this figure, the black circle indicates HR for the present state (HRP) and the white circle is for the

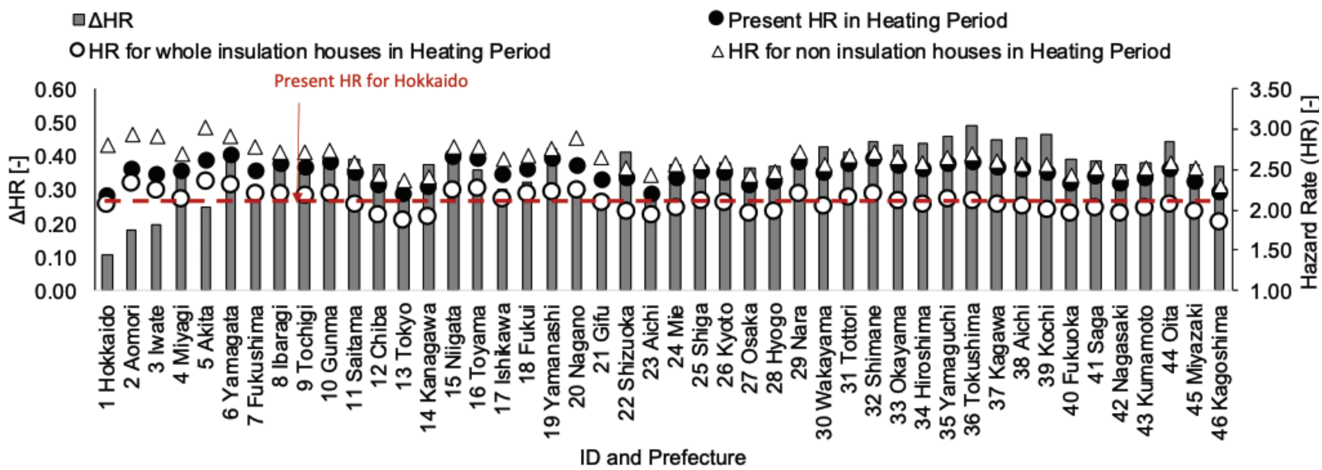

Fig. 12. Relationship between HRs of both the no-insulation residential houses and the suitable insulation residential houses.

idealized case (HRI). The vertical bar also expresses the difference between HRP and HRI (ΔHR = HRP - HRI) for each prefecture. In this figure, the distributions of ΔHR range from approximately 0.10 to 0.49. In particular, the values of ΔHR for prefectures in both western Japan and north Kanto areas are quite large. This is because several residential houses with low insulation performance (insulation ranging from approximately 0.10 to 0.40) are located in those prefectures. As a result, converting all low-insulation houses in most prefectures to suitable insulation houses enables a reduction of HR to near or below the hazardous level of the current state in Hokkaido. In contrast, the ΔHR values in the north Tohoku area, such as in Aomori, Iwate, and Akita, are relatively small. In these prefectures, the present rate of insulation houses is over 60%. Then, the rate of renewing the insulation houses is small compared with that of other prefectures. Hence, in these prefectures, it is necessary to increase the number of houses with one step higher insulation performance.

5 Conclusion

In this study, the current state of the thermal environment in residential houses in Japan was evaluated using the BEST-H program, a computation tool for analysing the thermal load in residential houses. The computational method was described and the computation results validated. Using the proposed method, we conducted a numerical analysis based on the network analysis for the heat and ventilation in residential houses in each PSA in each prefecture in Japan. From these investigations, we observed that more houses with suitable insulation performance should be established in the western area and northern part of the Kanto area in Japan. These findings are expected to contribute to the future planning of suitable residential houses in Japan.

The following are topics for future study: The first is to consider the variations in residential house types. In the present study, the thermal environment in a typical residential house was evaluated. However, there are several types of residential houses regarding the insulation level, plan, volume, structure, lifestyle of residents, etc. As a result, we must collect useful and effective data and conduct further analysis with BEST-H program. The second is to apply the proposed method to evaluate other diseases in residential houses in Japan. For example, respiratory diseases in the winter season are a primary issue. Using the proposed method, this can be evaluated and practical countermeasures can be proposed, as respiratory diseases are affected by the thermal environment and air quality in houses. For this purpose, observational data should be collected for a quantitative relationship between thermal environment and respiratory diseases. The near future direction of our study is to evaluate variable countermeasures, such as one-room insulation.

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