E3S Web of Conferences **599**, 04004 (2024) https://doi.org/10.1051/e3sconf/202459904004
STACLIM 2024

Comfort band for adaptive model based on quadratic regression and probit analysis

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Abstract. Many researchers focus on developing adaptive models without concerning the comfort band as most of them only refer to the ASHRAE or other global standards. Therefore, a field measurement was conducted at a residential building in Tokyo, Japan for 2 years in order to develop the comfort band by using quadratic regression and probit analysis for the adaptive thermal comfort model. A total of 32,988 thermal sensation votes (TSV) from thermal comfort surveys were collected. The results showed that the mean thermal sensation vote was 4.0 in free-running (FR), 3.7 in heating (HT), and 4.2 in cooling (CL) modes which indicates that the residents were generally satisfied with the condition of indoor environment in the dwellings. This may be because the residents are well-adapted to the local climate and culture. The comfort temperature during FR, HT, and CL modes were 23.7ºC, 20.9ºC, and 26.8ºC, respectively. The mean and standard deviation of the difference between indoor and comfort temperature (ΔT) is 0.2±1.2°C. In developing the comfort band for the adaptive model in this study, quadratic regression and probit analysis utilized the data of ΔT. The appropriate comfort band was fixed as ±1.5°C and ±2.0°C for 90% and 80% limits of the comfort band. These results are crucial when creating reliable standards and guidelines for building design or indoor environmental quality assessment.

1 Introduction

The first worldwide standard that includes the model of adaptive comfort to evaluate indoor thermal comfort is ANSI/ASHRAE Standard 55 [1]. This standard was proposed in response to de Dear and Brager's substantial work from 2002. They used the data gathered for the "naturally conditioned" buildings in ASHRAE project RP 884 [2]. Despite being an American national standard, ASHRAE 55's adaptive model is thought of as a global standard as the field studies for it came from various countries and areas. However, the worldwide standard does not include data from Japan. Moreover, the data included is mostly from office buildings. Currently, there is no official Japanese adaptive standard that can be relied on.

An adaptive model with country or region-specific data points is more indicative of the occupants' thermal preferences. Several researchers have been focused on constructing an

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adaptive thermal comfort model for their specific case study. For example, Takasu et al. [3] examined the adaptive models that can be applied to design the indoor thermal environment of Japanese office buildings under various operational modes. They found that the optimum comfort temperature range in mixed-mode is approximately 23.5°C to 26.6°C, with these values representing the lower and upper limits, respectively. In China, Yue and Zhongqing [4] investigated thermal comfort standard in residential buildings and established an adaptive thermal comfort model. However, most of the previous studies only referred to ASHRAE [5], CIBSE [6], or CEN [7] standards when providing upper and lower limits to the equation of the adaptive model. Therefore, in order to develop the comfort band for the adaptive model, this study utilized the data of the difference between indoor and comfort temperature (ΔT) instead of indoor air temperature (T_{in}). Rijal et al. [8] provided support for this at which they developed the deadband of temperature for window opening behaviour by with the use of ΔT as the data points. They mentioned that the width of the deadband can be narrower when utilizing the data of ΔT instead of T_{in} due to the higher seasonal differences in comfort temperatures.

Thus, to create a reliable standard and guidelines for architects and construction companies, data from Japanese dwellings need to be investigated for further analysis. The purposes of this study are to explore the distribution of thermal sensation votes for different operation modes, estimate comfort temperature by Griffiths' method, and develop the comfort band by using quadratic regression and probit analysis for adaptive thermal comfort model of Japanese houses.

2 Methodology

2.1 On-site measurement and thermal comfort survey

The investigated building is an 18-story condominium that could fit 356 households. The Katsushima condominium is composed of reinforced concrete and could feature 21 houses on each floor. The floor size varied from 71 to 90 m^2. On-site measurement and thermal comfort survey were carried out on 64 flat units. A data logger was utilized to monitor the indoor temperature and relative humidity, and illuminance in the living room at two-to-ten-minute intervals. It was positioned in the middle of the living room. On-site measurements and surveys were conducted between November 2015 and November 2017. Over the duration of the field survey, approximately 32,988 votes were submitted for free-running (FR), heating (HT), and cooling (CL) modes. An online questionnaire (Figure 1) was administered to the residents, covering questions on thermal sensation, thermal preference, and occupant behaviour, to record any thermal adjustments they made. The thermal comfort scale illustrated in Table 1 was employed.

2.2 Griffiths' method to estimate comfort temperature

To determine the comfortable temperature, Griffiths' approach was applied. Griffiths' method can construct an estimated link between temperature and comfort vote as the predicted comfort temperature is determined for each comfort vote [9]. Depending on the season, building design, and thermal adaption, the comfortable temperature may fluctuate [10]. Equation (1) shows the calculation of T_c by Griffiths method.

$$T_c = T_{in} + (4 - \text{TSV}) / \alpha \quad (1)$$

When a seven-point thermal sensation scale (ranging from 1 to 7) is used, a rating of '4' indicates a neutral condition. In this context, α, the Griffiths constant, is equivalent to the regression coefficient, and its value was fixed to be 0.50.

Fig. 1. Online questionnaire survey.

Table 1. Thermal sensation scale.

Scale	Thermal sensation
1	Very cold
2	Cold
3	Slightly cold
4	Neutral
5	Slightly hot
6	Hot
7	Very hot

2.3 Quadratic regression and probit analysis

The range of comfort zones can be investigated by using quadratic regression as the two variables have a non-linear relationship. The goal is to fit a quadratic equation to the observed data, providing an advanced model of the relationship. The equation below can be used to explain or predict certain outcomes from quadratic regression.

$$P_{comf} = ax^2 + bx + c \qquad (2)$$

Where P_{comf} is the proportion of comfort zone from quadratic regression, 'x' is the variable and a, b, and c are the coefficients of the quadratic equation.

Probit analysis was applied to TSV categories and indoor air temperature to determine the comfort zone. It is generally recognized in thermal comfort research that if occupants in naturally ventilated buildings choose thermal sensation scale categories within the comfort zone (TSV = 3, 4, 5), they are considered to be in a state of comfortable. Equation (3) was used in order to transform the Probits into the proportion.

$$\text{Probability} = \text{CDF.NORMAL (quant, mean, SD)} \quad (3)$$

Where 'CDF.NORMAL' is the Cumulative Distribution Function for the normal distribution. In this study, 'quant' is the T_{in} or ΔT, and SD is the standard deviation.

3 Results and discussion

3.1 Thermal sensation vote

Figure 2 shows the distribution of TSV of the residents according to different types of operation modes. It was mentioned that adjusting to an abrupt shift in temperature takes some time to reach the new thermal equilibrium [11]. This can be supported by Dahlan & Gital [12] which revealed that the shift in thermal sensation votes following a temperature change is contingent upon the temperature difference between the two environments. Thus, determining the distribution of thermal sensation votes depending on the operation modes is important. The mean thermal sensation was 4.0 in FR mode, 3.7 in HT mode and 4.2 in CL mode. It can be seen that, when residents used the cooling, they also sometimes felt "slightly hot". Residents also sometimes felt cold (<3) in the HT mode. As being shown in MM for the overall result, most of the voting was in the thermal comfort zone. Residents were mainly comfortable with the thermal environment in their homes. This might be due to the local's accustomed to the climate and culture of the area.

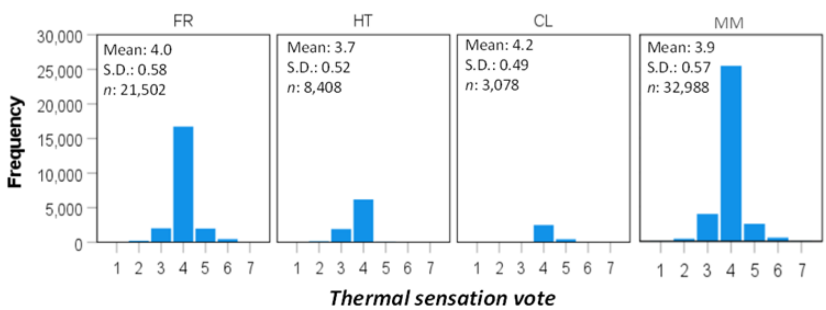

Fig. 2. Distribution of TSV in FR, HT, CL and MM mode.

3.2 Monthly variation of T_c and ΔT during FR mode

Examining how monthly temperature changes influence thermal comfort can offer important direction for the design of future buildings [13]. Figure 3 shows the monthly variation of T_c while Figure 4 shows the monthly variation of ΔT during FR mode by the representation of the error bar (mean ± 2S.E.). The mean comfort temperature during FR, CL, and HT modes were 23.7 ºC, 26.8 ºC, and 20.9 ºC respectively. Rijal et al. [14], highlighted that the comfort temperature was found to be 25.0 ±1.7°C (FR mode), 25.4±1.5°C (CL mode), and 24.3± 1.6°C (HT mode) which are similar to this study. As for the variations of ΔT, the highest and lowest were during August (2ºC) and December (-0.5ºC). The average value of the ΔT is 0.2°C, with the standard deviation of ±1.2°C.

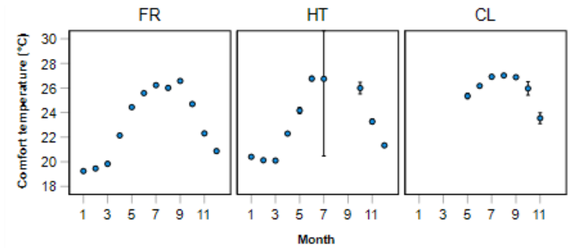

Fig. 3. Monthly variation of T_c in FR, HT, and CL mode with 95% confidence interval.

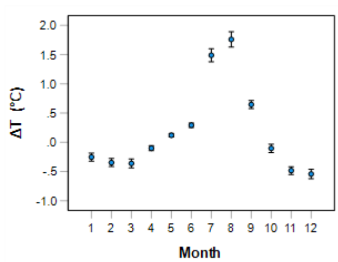

Fig. 4. Monthly variation of ΔT in FR model 95% confidence interval.

3.3 Comfort band by quadratic regression and probit analysis

In order to conduct the quadratic regression analysis, the comfort scale was adjusted into a binary format (0,1). The values "1. Very cold," "2. Cold," "6. Hot," and "7. Very hot" were classified as uncomfortable and assigned a value of 0, whereas the remaining categories were classified as comfortable and coded as 1. Figure 5 shows the proportion of comfort zone for the data of T_{in} by using quadratic regression and probit analysis. The quadratic equations are as shown below.

$$P_{comf} = -0.0027T_{in}^2 + 0.113T_{in} - 0.2 \tag{4}$$

(N= 21502, R^2=0.05, S.E.$_1$=0.001, S.E.$_2$=0.008, p<0.001)

Where P_{comf}: Proportion of comfort zone, N: number of sample, S.E.$_1$: standard error of the regression coefficient for $T_{in}{}^2$, S.E.$_2$: standard error for of the regression coefficient for T_{in}, p: significance level of regression coefficient.

When using the data of T_{in} at 0.8 proportion of comfort, the comfort range is 12.7 to 29.1°C which makes the range of the band is 16.4°C. Thus, the comfort band is ±8.2°C for each upper and lower limit. Regarding the probit analysis, the comfort vote's bell curve can be obtained by converting the probits into the percentage of votes for the three center categories (votes 3, 4, and 5) (Table 2). It suggests that 14.5 to 28ºC is the range that 80% of people feel comfortable. The comfort band when using the data of T_{in} is ±6.8ºC. The band is much wider than any global comfort band as the data of T_{in} covered the temperature for the whole seasons throughout the year. The proportion of comfort zone for the data of ΔT by using quadratic regression and probit analysis was shown in Figure 6. The quadratic equations are as shown below.

$$P_{comf} = -0.05\Delta T^2 + 0.003\Delta T - 1.0 \tag{5}$$

(N= 21502, R^2=0.8, S.E.$_1$=0.001, S.E.$_2$=0.001, p<0.001)

Where S.E.$_1$: standard error of the regression coefficient for ΔT^2, S.E.$_2$: standard error of the regression coefficient for ΔT.

When using the data of ΔT at 0.8 proportion of comfort, the comfort range is from -2 to +2°C and -2.2 to +2.2°C by using the quadratic regression and probit analysis, respectively. Results for the development of 80% and 90% limits of comfort band are listed in Tables 3 and 4. The band is narrower when using the data of ΔT as the temperature involved is only at a particular time. Both methods produced a similar value for the comfort band by using ΔT which justifies the appropriate method of using ΔT instead of T_{in}.

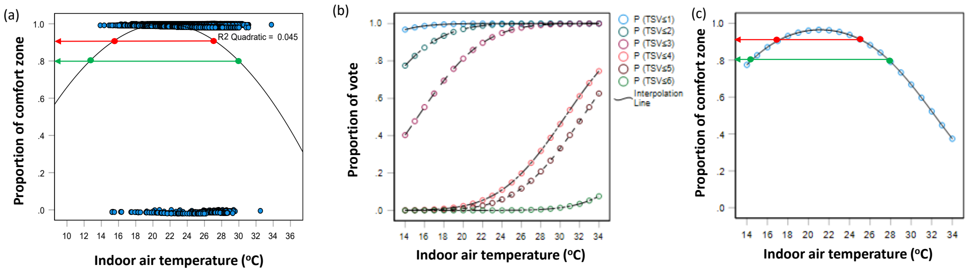

Fig. 5. Proportion of comfort zone for T_{in} by (a) quadratic regression and (b), (c) probit analysis during FR mode.

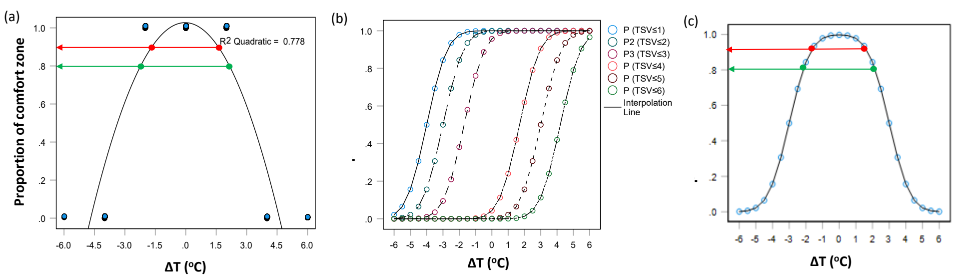

Fig. 6. Proportion of comfort zone for ΔT by (a) quadratic regression and (b), (c) probit analysis during FR mode.

Table 2. Results of probit analysis with data of T_{in} and ΔT.

Indices	Equation	Mean (°C)	S.D. (°C)	N	R^2	S.E.
T_{in}	TSV≤1=0.19T_{in}-0.8	4.2	5.3	11566	0.2	0.004
	TSV≤2=0.19T_{in}-1.9	10.0				
	TSV≤3=0.19T_{in}-2.9	15.3				
	TSV≤4=0.19T_{in}-5.8	30.5				
	TSV≤5=0.19T_{in}-6.7	35.3				
	TSV≤6=0.19T_{in}-7.9	41.6				
ΔT	TSV≤1=1.01ΔT+4.0	-4.0	1.0	11566	0.8	0.013
	TSV≤2=1.01ΔT+3.0	-3.0				
	TSV≤3=1.01ΔT+1.7	-1.7				
	TSV≤4=1.01ΔT-1.7	1.6				
	TSV≤5=1.01ΔT-3.0	3.0				
	TSV≤6=1.01ΔT-4.2	4.2				

Table 3. Comfort band by using data of T_{in}.

Method	Limit (%)	Lower, L (°C)	Upper, U (°C)	Difference, U-L (°C)	Comfort band (°C)

Quadratic	80	12.7	29.1	16.4	±8.2
	90	15.4	26.4	11.0	±5.5
Probit	80	14.5	28.0	13.5	±6.8
	90	17.0	25.5	8.5	±4.3

Table 4. Comfort band by using data of *ΔT*.

Method	Limit (%)	Lower, L (ºC)	Upper, U (ºC)	Proposed comfort band (ºC)
Quadratic	80	-2.0	2.0	±2.0
	90	-1.4	1.4	±1.5
Probit	80	-2.2	2.2	±2.0
	90	-1.7	1.7	±1.5

3.4 Adaptive model with proposed comfort band

The adaptive thermal comfort model for Japanese residential buildings during FR mode is presented in Figure 7. The equation for the model is as shown below:

$$T_c = 0.38T_{rm} + 16.91 \quad (6)$$

$$(N=11566,\ R^2=0.67,\ S.E.=0.003,\ p<0.001)$$

Where T_c represented comfort temperature calculated using Griffiths method (°C); T_{rm} denotes the exponentially weighted running mean outdoor temperature for the day (°C). The model also points out the proposed 80% (±2.0ºC) and 90% (±1.5ºC) of the comfort band limits. The running mean outdoor temperature was calculated with 0.8 as the time constant. Comparing this model to the model from ASHRAE [1], the acceptability band is ±3.5ºC and ±2.5ºC for 80% and 90% limits, respectively. The differences might be due to the climate experienced and types of buildings, since this study focuses on residential buildings, where the residents have the freedom to adjust to their environment when they feel uncomfortable.

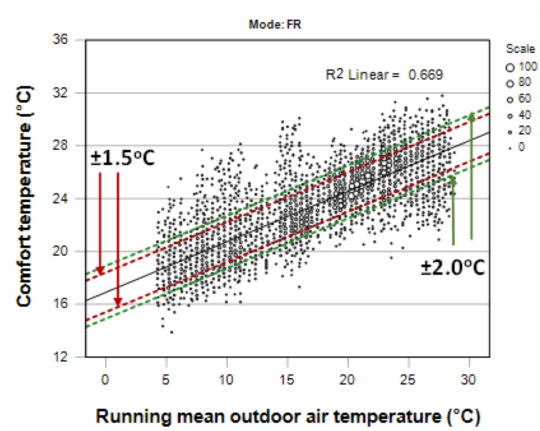

Fig. 7. Adaptive model with proposed comfort band.

4 Conclusions

The exploration on the development of comfort bands for adaptive models in Japanese residential buildings is still highly required. The following is a summary of the study's main conclusions:

1. For FR, HT, and CL modes, the mean thermal sensation values were 4.0, 3.7, and 4.2, respectively. Residents were mainly comfortable with the thermal environment in their homes. This could be because the locals are accustomed to the local climate and culture.
2. The mean T_c during FR, HT, and CL modes were 23.7 ºC, 20.9 ºC, and 26.8 ºC, respectively and the mean with standard deviations of ΔT is 0.2±1.2°C.
3. Both quadratic regression and probit analysis produced similar comfort bands when using the data of ΔT. Thus, the appropriate comfort band was found as ±1.5°C and ±2.0°C for 90% and 80% comfort band for the adaptive model.
4. The regression coefficient for the adaptive model in this study (0.38) is higher than the ASHRAE standard (0.31).

As the development of comfort band for adaptive model by using the data of ΔT has not been fully explored previously, these new methods of comfort bands are crucial when creating a reliable standard and guidelines for building design or indoor environmental quality assessment.

We express our gratitude to the households who took part in the survey. The Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) provided funding for this study under the "Subsidy for Pioneering Project about CO_2 emission reduction in residential and commercial building II, 2013."

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