Study on behavioral adaptation for the adaptive thermal comfort and energy saving in Japanese office buildings

Hom Bahadur Rijal[1*], Supriya Khadka[1], Katsunori Amano[2], Teruyuki Saito[3], Hikaru Imagawa[4], Tomoko Tomoko[5], Kahori Genjo[6], Takata Takata[7], Kazuyo Tsuzuki[8], Takashi Nakaya[9], Daisaku Nishina[10], Kenichi Hasegawa[11], Taro Mori[12]

1: Tokyo City University, Tokyo, Japan; 2: Haseko Corporation, Tokyo, Japan;
3: Nagoya University, Nagoya, Japan; 4: Osaka Institute of Technology, Osaka, Japan;
5: Mukogawa Women's University, Hyogo, Japan; 6: Nagasaki University, Nagasaki, Japan;
7: Hiroshima Institute of Technology, Hiroshima, Japan; 8: Kansai University, Osaka, Japan;
9: Shinshu University, Matsumoto, Japan; 10: Hiroshima University, Hiroshima, Japan;
11: Akita Prefectural University, Akita, Japan; 12: Hokkaido University, Hokkaido, Japan

rijal@tcu.ac.jp

Abstract

Office workers use a variety of adaptive opportunities to regulate their indoor thermal environment. The behavioural adaptations such as window opening, clothing adjustments, and use of heating/cooling are important factors for adaptive thermal comfort. It is well-known that they are the most important contributors in the adaptive thermal comfort model. Thus, if we understand the behavioural adaptation properly, we can explain the mechanism of the adaptive model. The indoor thermal environment is often adjusted using the air conditioning in Japanese office buildings to improve thermal comfort and productivity. Thus, it is necessary to conduct research on the behavioural adaptation in the offices because the occupant behaviour is different from behaviour in dwellings. In order to record the seasonal differences in behavioural adaptation and to develop an adaptive algorithm for Japanese offices, we measured temperatures in seven office buildings and conducted the thermal comfort and occupant behaviour survey for over a year. We collected 1,228 samples. The proportion of 'open windows' is significantly high in the free running and air conditioned modes. The behavioural adaptation is related to the outdoor air temperature. The clothing adjustments, heating and cooling use can be predicted by regression equations. These findings can be applied to building thermal simulation to predict the behavioural adaptation and energy use in office buildings.

Keywords - Office buildings, Occupant behaviour, Window opening, Clothing adjustment, Heating and cooling use.

1. Introduction

People use a variety of adaptive opportunities to regulate their indoor thermal environment. The behavioural adaptations such as window opening, clothing adjustments, heating/cooling use are some of the important factors for adaptive thermal comfort. It is well-known that they are the most important contributors in the adaptive thermal comfort model. Thus, if we understand the behavioural adaptation properly, we can explain much of the mechanism of the adaptive model. In addition, the indoor thermal environment is often adjusted using the air conditioning in the Japanese office building to improve the thermal comfort and productivity. However, temperature control using window opening can reduce environmental impact by reducing the use of air conditioning as much as possible. Thus, it is necessary to conduct research on the behavioural adaptation in the offices because the occupant behaviour is different from adaptive behaviour in dwellings.

A number of projects have researched occupant behaviour in offices [1-12], and dwellings [13-20]. The occupant behaviour model developed for office buildings in other countries [3] may not apply to Japan and research about occupant behaviour is needed for Japanese offices, for results from one region of the world cannot be assumed to apply to another where there is a different culture and building design. Thermal simulation packages often assume a fixed schedule of window opening [4], so more realistic data on occupant behaviour will help to improve the thermal simulations and an adaptive algorithm becomes a useful passive design tool. In order to record the seasonal differences in behavioural adaptation and to develop adaptive algorithms for Japanese offices, we measured temperatures in seven office buildings and conducted occupant behaviour surveys for over a year in the Aichi prefecture of Japan.

2. Methods

2.1 Field Survey

Occupant surveys were conducted and corresponding thermal measurements made in seven office buildings in the Aichi prefecture of Japan from July 2021 to October 2022 (see Table 1). The indoor air temperature, globe temperature, relative humidity and air movement were measured 1.1m above floor level, away from direct sunlight, using a data logger (Table 2). Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

Table 1: Description of the investigated buildings [21, 22]

Building code	Location	Structure	Mode	HVAC control	Window	Number of floor	Investigated floor*
N1	Ichinomiya	SRC	MM	Local	Openable	3F	2F
N2	Nagoya	RC	MM	Local	Openable	6F	1F~3F
N3	Nagoya	SRC	HVAC	Central (Local control)	Openable (For disaster prevention)	1B, 8F	4F
N4	Nagoya	SRC	MM	Local	Openable	1B, 5F	2F
N5	Nagoya	SRC	MM	Local	Openable	1B, 17F	4F
N6	Nagoya	S, Some parts SRC	HVAC	Central (local control)	Fixed	4B, 34F	27F
N7	Nagoya	RC	MM	Local	Openable	1B, 8F	5F

HVAC: Heating, ventilation and air conditioning, MM: Mixed mode (heating in winter and cooling in summer), *: The floor is counted by American system, SRC: Steel Reinforced Concrete, RC: Reinforced concrete, S: Steel, F: Floor, B: Basement

We conducted both longitudinal [21] and transverse surveys [22] in open-plan offices. This paper analyses only the data from the transverse survey. Transverse surveys were conducted 1 day each month by researchers visiting each building with measurement instruments and with questionnaires filled by each subject. On each visit, one set of responses was collected from each subject. As for the method of collecting the data, the instruments were set up on the office table, and questionnaires distributed to all people seated near to the instruments. While people were filling the questionnaire, the researcher recorded the common environmental controls and the physical data from them. Window opening, heating use and cooling use were recorded in binary form at the time of completing the questionnaire (0 = window closed or heating/cooling off, 1 = window open or heating/cooling on). We collected 1,228 votes.

Table 2: Description of the instruments

Parameter measured	Trade name	Range	Accuracy
Air temperature, Relative humidity (RH)	TR-76Ui	0 to 55 °C, 10% to 95% RH	±0.5 °C, ±5%RH
Globe temperature	Tr-52i	−60 to 155 °C	±0.3 °C
	SIBATA 080340-75	Black painted 75 mm diameter globe	-

2.2 Estimating the Occupant Behaviour

Nicol and Humphreys [3] made use of logistic analysis to predict occupant control behaviour in naturally ventilated buildings. We have adopted this method here, using SPSS version 23 for the calculations. The relationship between the probability of heating use or cooling use (p) and the outdoor air temperature (To) is of the form:

$$\mathrm{logit}(p) = \log\{p/(1-p)\} = bT_o + c \quad (1)$$

$$p = \exp(bT_o + c)/\{1 + \exp(bT_o + c)\} \quad (2)$$

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

3. Results and Discussion

The data were divided into three groups. If heating was in use at the time of the survey visit, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the visit, the data were classified as being in the cooling mode (CL). If neither heating or cooling were in use, the data were classified as being in the freerunning mode (FR).

3.1 Outdoor and Indoor Temperature during the Voting

As shown in Figure 1, the seasonal range of the indoor temperature was quite small, while there was a wide seasonal range of outdoor temperature. The indoor globe temperature is highly related to the indoor air temperature [22], and so the results can be presented using the globe temperature alone. The mean globe temperatures during the voting were 25.0 °C, 24.2 °C and 25.5 °C for FR, HT and CL modes respectively [22]. The Japanese government recommends indoor temperature of 20 °C in winter and 28 °C in summer for energy saving respectively. The results showed that the mean indoor temperatures during heating and cooling were quite different from those recommended values.

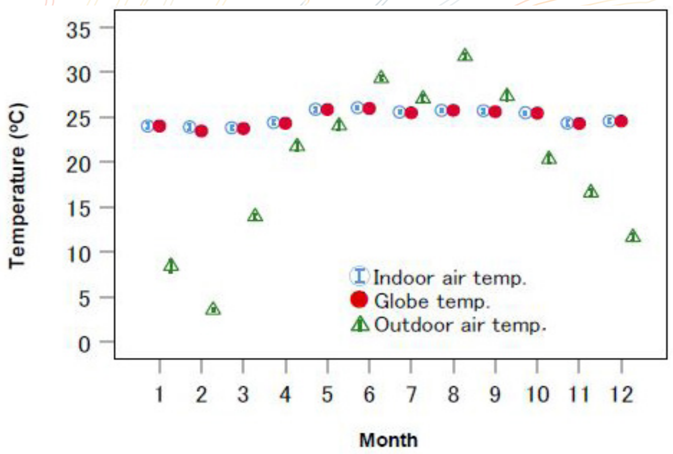

Figure 1: Variation of outdoor and indoor temperatures (Mean±2S.E.) [22].

3.2 Window Opening Behaviour

Figure 2 shows the proportion of window opening in mixed mode buildings. The mean 'open window' for all data is 0.59 (n=1,022). When we compared by building, the mean value ranged from 0.50 to 0.80. The mean window opening is 0.68, 0.59 and 0.48 for FR, HT and CL modes respectively. The mean window opening in UK office buildings was 0.70 in NV mode and 0.04 in AC mode [4]. The mean windows open in Pakistan office and commercial buildings was 0.33 in NV mode [5]. The results showed that the mean windows open in FR mode is close to the UK and much higher than the Pakistan. Due to the COVID-19, the window opening is very high in the HT and CL modes. During the COVID- 19 pandemic, guidance has been issued by Japanese authorities that windows must be left open in many building types, even when the AC is in use, to purge spaces of the virus, because many HVAC systems recycle air from room to room, so increasing the risk of cross transmission of the pathogen indoors [10, 23-25].

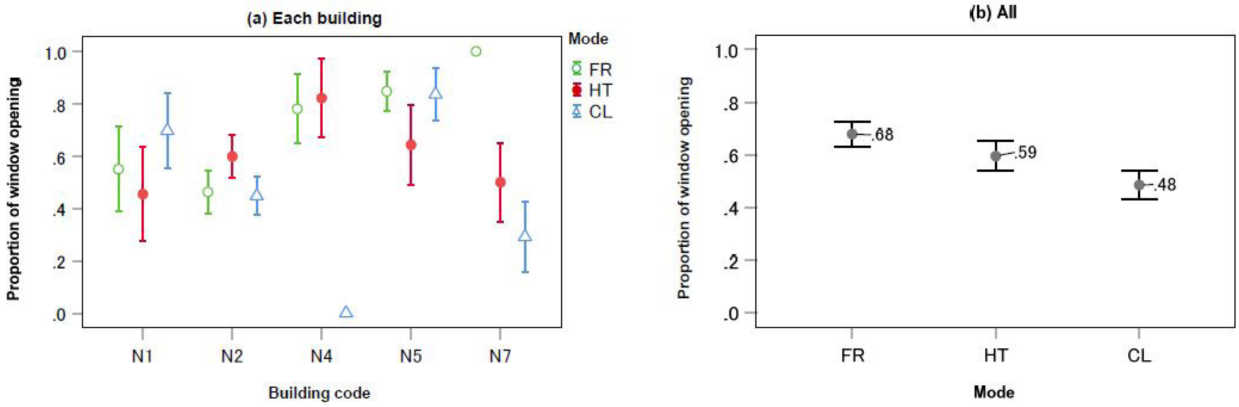

Figure 2: Proportion of window opening in mixed mode buildings

3.3 Clothing Adjustments

Figure 3 shows the mean clothing insulation by mode in mixed mode building. The mean clothing is 0.73 clo in FR mode which is slightly higher than CL mode and lower than HT mode. The results show that people adjusted their clothing considerably in each mode.

In order to predict the clothing insulation, regression analysis of the clothing insulation and outdoor air temperature is conducted. Figure 4 shows the relation between the clothing insulation and outdoor air temperature with the 95% confidence interval of the individual clo-values in MM and HVAC buildings. The following regression equations were obtained between the clothing insulation (Icl, clo) and outdoor temperature.

MM $I_{cl}=-0.02T_o+1.2$ (n = 41030, $R^2 = 0.40$, S.E. = 0.001, $p<0.001$) (3)

HVAC $I_{cl}=-0.01T_o+01.0$ (n = 196, $R^2 = 0.27$, S.E. = 0.0001, $p<0.001$) (4)

All $I_{cl}=-0.02T_o+1.1$ (n = 1226, $R^2 = 0.37$, S.E. = 0.001, $p<0.001$) (5)

R^2 is the coefficient of determination. The regression coefficients are negative for all equations. It shows that the clothing insulation decreases when outdoor air temperature is increased.

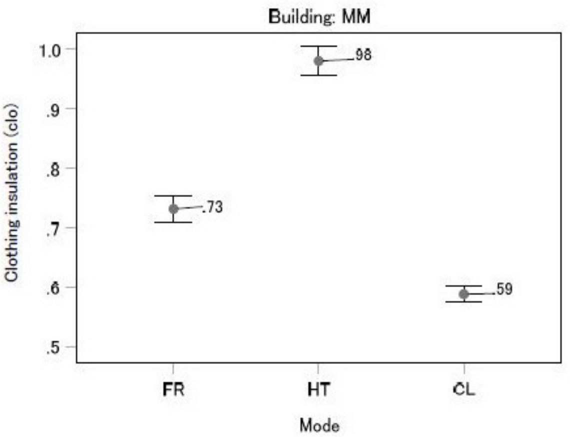

Figure 3: Clothing insulation by mode in the mixed mode buildings (Mean±2S.E.).

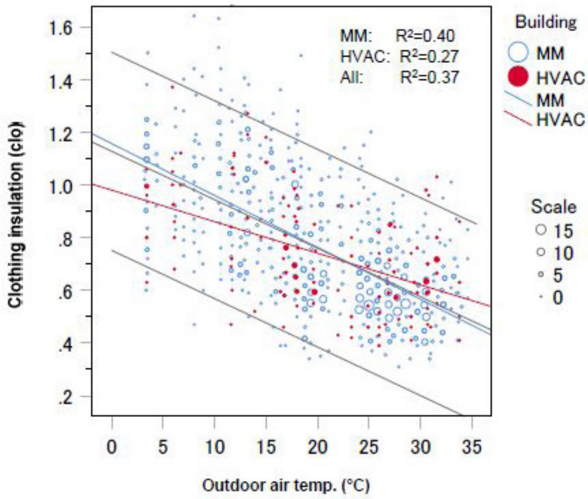

Figure 4: Relation between the clothing insulation and outdoor air temperature.

3.4 Heating and Cooling Use

In this section, we will analyse the heating and cooling use. These behaviours are needed for the thermal simulation of buildings. Table 3 shows the logistic regression equations obtained for each building and all data in between the heating use or cooling use and the outdoor air temperature. These equations are presented in Figure 5. The proportion of the heating use rises as the outdoor temperature decreases, and the proportion of the cooling use rises as the outdoor temperature increases.

Table 3: Regression equations for heating and cooling use

Behaviour	Building	Equation	n	S.E.	R^{2*}	p
Heating	N2	logit(p)=-0.511T_o+8.4	474	0.051	0.55	<0.001
	N4	logit(p)=-0.635T_o+7.3	95	0.158	0.58	<0.001
	N5	logit(p)=-1.169T_o+18.1	189	0.238	0.52	<0.001
	N7	logit(p)=-0.627T_o+8.6	146	0.137	0.59	<0.001
	All	logit(p)=-0.530T_o+8.1	1022	0.038	0.54	<0.001
Cooling	N1	logit(p)=0.431T_o-11.5	116	0.089	0.44	<0.001
	N2	logit(p)=0.810T_o-19.9	474	0.094	0.60	<0.001
	N5	logit(p)=695T_o-18.0	186	0.141	0.61	<0.001
	N7	logit(p)=1.123T_o-28.4	148	0.364	0.63	<0.001
	All	logit(p)=0.688T_o-17.2	1019	0.053	0.58	0.002

T_o: Outdoor air temperature (°C), n: Number of sample, S.E.: Standard error of regression coefficient, R^2*: Cox and Snell R^2, p: Significance-level of the regression coefficient.

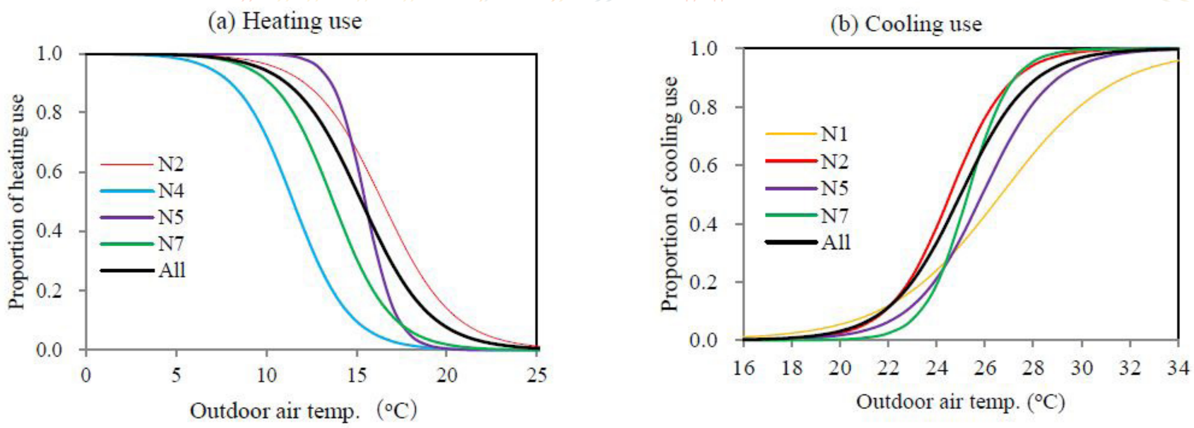

Figure 5: Proportion of window opening in mixed mode buildings.

4. Conclusions

We have conducted occupant behaviour surveys in seven Japanese office buildings. The following results were found:

- Due to the COVID-19, the proportion of 'open windows' is high in free running, heating and cooling modes.

- The behavioural adaptations (clothing adjustments and heating/cooling use) are related to the outdoor air temperature.

- The occupant behavioural models can be applied to building thermal simulation to predict the behavioural adaptation, indoor temperature and energy use in office buildings.

5. Acknowledgements

We would like to sincerely thank to the Itsuwa Denki Kogyo Co., Ltd., Kimura Kohki Co., Ltd., SEEDS Co., Ltd., Shinwa Electric Co., Ltd., Yasui Architects & Engineers, Inc. and local government for their kind cooperation. This research is supported by the Grant-in-Aid for Scientific Research (B) (21H01496).

6. References

[2] Brager, G.S., Paliaga, G. & de Dear, R. (2004). Operable windows, personal control, and occupant comfort. ASHRAE Transactions 110(2), pp. 17-35.

[3] Kim, J., Kawaguchi, T., & Tanabe, S. (2009). The behavioral characteristic of office workers use of natural ventilation window. J. Environ. Eng., AIJ 74 (643), pp. 1075-1082.

[4] Nicol, J.F., & Humphreys, M.A. (2004). A stochastic approach to thermal comfort – Occupant behavior and energy use in buildings. ASHRAE Transactions 110(2), pp. 554-568.

[5] Rijal, H.B., Tuohy, P., Humphreys, M.A., Nicol, J.F., Samuel, A., & Clarke, J. (2007). Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy and Buildings 39(7), pp. 823-836.

[6] Rijal, H.B., Tuohy, P., Humphreys, M.A., Nicol, J.F., Samuel, A., Raja, I.A. & Clarke, J. (2008). Development of adaptive algorithms for the operation of windows, fans and doors to predict thermal comfort and energy use in Pakistani buildings. ASHRAE Transactions 114 (2), pp. 555-573.

[7] Rijal, H.B., Tuohy, P., Nicol, F., Humphreys, M.A., Samuel, A., & Clarke, J. (2008). Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. Journal of Building Performance Simulation 1 (1), pp. 17-30.

[8] Rijal, H.B., Tuohy, P., Humphreys, M.A., Nicol, J.F., & Samuel, A. (2011). An algorithm to represent occupant use of windows and fans including situation-specific motivations and constraints. Building Simulation 4 (2), pp. 117-134.

[9] Rijal, H.B., Tuohy, P., Humphreys, M.A., Nicol, J.F., & Samuel, A. (2012). Considering the impact of situation-specific motivations and constraints in the design of naturally ventilated and hybrid buildings. Architectural Science Review 55(1), pp. 35–48.

[10] Rijal, H.B., Humphreys, M.A., & Nicol, J.F. (2019). Behavioural adaptation for the thermal comfort and energy saving in Japanese offices. Journal of the Institute of Engineering 15 (2), pp. 14-25.

[11] Rijal, H.B., Humphreys, M.A., & Nicol, J.F. (2022). Chapter 17 Adaptive approaches to enhancing resilient thermal comfort in Japanese offices. In: Nicol, F., Rijal, H.B., & Roaf, S., eds. Routledge Handbook of Resilient Thermal Comfort, Edited by, London: Routledge, ISBN 9781032155975, pp. 279-299.

[12] Shahzad, S., & Rijal, H.B. (2022). Chapter 20 Mixed mode is better than air conditioned offices for resilient comfort: Adaptive behaviour and visual thermal landscaping. In: Nicol, F., Rijal, H.B., & Roaf, S., eds. Routledge Handbook of Resilient Thermal Comfort, London: Routledge, ISBN 9781032155975, pp. 329-346.

[13] Genjo, K., Nakanishi, H., Oki, M., Imagawa, H., Uno, T., Saito, T., Takata, H., Tsuzuki, K., Nakaya, T., Nishina, D., Hasegawa, K., Mori, T., & Rijal, H.B. (2023). Development of adaptive model and occupant behavior model in four office buildings in Nagasaki, Japan. Energies 16(16), 6060.

[14] Asawa, T., Hoyano, A., Takezawa, H., & Shimizu, K. (2005). Analysis of the behavioral characteristics of both window opening and air conditioning use at detached houses: Relationship between outdoor microclimate and residents' living open to outdoor part 2. J. Environ., Eng., AIJ 593, pp. 87-94.

[15] Majima, M., Umemiya, N., Yoshida, H., & Rijal, H.B. (2007). Thermal comfort of traditional narrow alleys in an urban area: Survey for Nishijin district in Kyoto. J. Environ., Eng., AIJ 622, pp. 41-48.

[16] Kubota, T. (2007). A field survey on usage of air-conditioners and windows in apartment houses in Johor Bahru city. J. Environ. Eng., AIJ 616, pp. 83-89.

[17] Rijal, H.B., Honjo, M., Kobayashi, R., & Nakaya, T. (2013). Investigation of comfort temperature, adaptive model and the window opening behavior in Japanese houses. Architectural Science Review, 56(1), pp. 54-69.

[18] Imagawa, H., & Rijal, H.B. (2015). Field survey of the thermal comfort, quality of sleep and typical occupant behaviour in the bedrooms of Japanese houses during the hot and humid season. Architectural Science Review 58(1), pp. 11-23

[19] Rijal, H.B., Humphreys, M., & Nicol, F. (2015). Adaptive thermal comfort in Japanese houses during the summer season: Behavioral adaptation and the effect of humidity. Buildings 5(3), pp. 1037-1054

[20] Rijal, H.B., Humphreys, M.A., & Nicol, J.F. (2018). Development of a window opening algorithm based on adaptive thermal comfort to predict occupant behavior in Japanese dwellings. Japan Architectural Review 1(3), pp. 310-321.

[21] Rijal, H.B., Humphreys, M.A., & Nicol, J.F. (2019). Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings. Energy & Buildings 202, 109371.

[22] Khadka, S., Rijal, H.B., Amano, K., Saito, T., Imagawa, H., Uno, T., Genjo, K., Takata, H., Tsuzuki, K., Nakaya, T., Nishina, D., Hasegawa, K. & Mori, T. (2022). Study on winter comfort temperature in mixed mode and HVAC office buildings in Japan. Energies, 15(19), 7331.

[23] Rijal, H.B., Okamoto, S., Khadka, S., Amano, K., Saito, T., Imagawa, H., Uno, T., Genjo, K., Takata, H., Tsuzuki, K., Nakaya, T., Nishina, D., Hasegawa, K., & Mori, T. (2023). Development of the adaptive model for thermal comfort in office buildings of Aichi prefecture, Japan. E3S Web of Conferences 396, 01062, IAQVEC 2023. https://doi.org/10.1051/e3sconf/202339601062

[24] Hayashi, M., Yanagi, U., Azuma, K., Kagi, N., Ogata, M., Morimoto, S., Hayama, H., Mori, T., Kikuta, K., Tanabe, S., Kurabuchi, T., Yamada, H., Kobayashi, K., Kim, H., & Kaihara, N. (2020). Measures against COVID-19 concerning summer indoor environment in Japan. Japan Architectural Review, 3(4), pp. 423– 434.

[25] Kurabuchi, T., Yanagi, U., Ogata, M., Otsuka, M., Kagi, N., Yamamoto, Y., Hayashi, M., & Tanabe, S. (2021). Operation of air- conditioning and sanitary equipment for SARS-CoV-2 infectious disease control. Japan Architectural Review, 4(4), pp. 608–620.

[26] SHASE (The Society of Heating, Air- Conditioning and Sanitary Engineers of Japan), (AIJ) Architectural Institute of Japan, 2020. Role of ventilation in the control of the COVID-19 infection: Emergency presidential discourse. http://www.shasej.org/base.html?recommendation/covid-19/co