Development of Single and Combined Fan-Use Models in Japanese Dwellings

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Abstract. Thermal adjustment is one of the most important behaviours. In daily life, we use some behavioural adjustments for thermal comfort. Especially, fan use is most common adaptive behaviour for the active thermal adjustments. The occupant behaviour stochastic models were proposed by some previous studies. However, the relative proportion of each behaviour has not yet been fully understand. It is important to estimate the proportion of each behaviour relatively because the selection of behaviour is determined in relation to each others. In our previous study, the stochastic models of window opening/closed, cooling and heating use were integrated to one model. The integrated fan use model is useful for understanding the occupant behaviour. The objective of this research is to clarify the fan use in relation to the window opening and cooling use. The occupant behaviour surveys were conducted in 120 dwellings during a four-year period in Kanto region of Japan. From this survey, we have collected 36,114 responses. The major findings are: 1) The proportion of fan use was highest in summer; 2) The stochastic model of fan use was explained by outdoor air temperature, and the combined stochastic model of “fan use” and “window opening or cooling use” were also developed; and 3) The proportion of “combined fan use” was higher than that of “fan single use”. The results indicated that the residents use the fan together with some other thermal adjustments. The knowledge of this research, as the next step of research, will be implemented in building thermal simulation.

1. Introduction
Thermal adjustment is one of the most important behaviour. In daily life, we always take some adjustments suitable not only to health but also to thermal comfort. Japan has 4 seasons including very distinctive summer and winter. Therefore, Japanese people usually take some adjustment depending on respective season.

In Japanese dwellings, standing fans and air conditioner are the common electric appliances for thermal adjustment. Air conditioners are spread about 90% in Japanese dwellings [1]. In addition, fans are also spread; it was about 95% already in 1985 [2]. A previous study [3] showed that the comfort temperature can be increased about 3°C by 0.8 m/s of air movement. Therefore, it is important to quantify the fan use behaviour.

In previous studies, stochastic occupant behavioural models were analysed all over the world. There are many previous studies on clothing adjustment, window opening/closed, air conditioner and fan use and others [4-13]. The models were developed for each behaviour. However, most of the occupant
behaviours are not taken independently but in relation to other occupant behaviours. For example, when the residents use an air conditioner in the dwelling, the windows are usually closed for energy saving.

Thus, the window opening/closed and the cooling or heating use by air conditioner were integrated into one model in our previous studies [10-12]. However, this integrated model does not include other occupant behaviours. If we integrate other behaviours into one model, then it leads to quantifying the residents’ overall life style. By such development, we can simulate that the residents’ use of fan with window opening or cooling use and also that with air conditioner; it is because the fan use may not be necessarily prevented by window opening or air conditioning use. In some previous studies, the fan use model was shown without a combined use [4, 6, 7]. But, we think that it is important to clarify the relation between the fan use and window opening/air conditioning use.

The objective of this research is to clarify the fan use in relation to the window opening and cooling use. The stochastic occupant behavioural model is useful for not only understanding the residents’ life style but also have a better understanding of more realistic energy use by implementing the resident’s behaviour algorithm in building thermal simulation models. The integrated model may improve the accuracy of the simulation results.

2. Survey Methods

2.1. Field Survey

We have conducted a series of field survey in 120 Japanese dwellings in Kanto region of Japan. The number of subjective was 120 residents. The period was from 6th July 2010 to 9th August 2014 [13]. In this survey, we conducted the thermal environment measurement and the thermal comfort survey simultaneously. We measured the indoor air temperature and relative humidity in 10 minute intervals. When the residents voted their thermal comfort, they also answered the states of the window opening/closed, cooling or heating by air conditioner and fan use. These adjustment states were recorded on binary data (opening or closed of window, use or no use of cooling, heating and fan). We have collected altogether 36154 responses.

The outdoor air temperature was obtained from the Japan meteorological station [14]. Figure 1 shows monthly mean outdoor air temperature during the survey period (from July 2010 to August 2014) in Tokyo meteorological station. The outdoor air temperature was highest in August (28.6°C), and the lowest in January (5.4°C). The range of outdoor air temperature is 23.2°C. From these, we confirm that Kanto region has both of hot, humid summer and cold, dry winter.

- Figure 1 Trend of the monthly mean outdoor air temperature and relative humidity in each month

2.2. Logistic Regression Analysis

Stochastic occupant behavioural model are usually modeled by applying so-called logistic regression equation [7-13] expressed an follows.

\[ \text{logit}(P) = \ln\left(\frac{p}{1-p}\right) = aT_o + b \]

(1)
where $P$ is the proportion of those taking a behaviour in question and $T_o$ is outdoor air temperature [$^\circ$C].

$$P = \frac{\exp(aT_o+b)}{1+\exp(aT_o+b)} (2)$$

$P$ as the proportion is in the range: $0<P<1$, but for realistic range of outdoor air temperature, the highest value of $P$ could not reach unity; that is, $P=1$. For these cases, we modify the maximum proportion to be unity as will be described in the following section.

3. Results and Discussions

3.1. Outdoor and Indoor Air Temperature

Figure 2 shows the mean outdoor and indoor air temperature during the voting. The outdoor air temperature ranges from 4.8°C in January and 28.0°C in August, and their difference is 23.2°C. Similarly, the indoor air temperature ranges from 16.5°C in February and 28.4°C in August, and their difference is 11.9°C. This is due to the effects of thermal insulation and mean together with the residents’ behaviour such as keeping the window closed in winter.

Figure 3 shows the relationship between indoor and outdoor air temperature in each mode. In this case, the data were categorised into 3 modes: FR mode (free running – no cooling or heating being used), CL mode (cooling use) and HT mode (heating use). The dotted lines represent diagonal, that is, $T_i=T_o$.

We obtained the following equations from the regression analysis.

**FR:** $T_i=0.587T_o+12.6$ (n=25180, $R^2=0.785$, S.E.=0.002, p<0.001) (3)

**CL:** $T_i=0.183T_o+22.3$ (n=6531, $R^2=0.069$, S.E.=0.008, p<0.001) (4)

**HT:** $T_i=0.220T_o+17.4$ (n=3582, $R^2=0.095$, S.E.=0.011, p<0.001) (5)

where $T_i$ is the indoor air temperature [$^\circ$C]. n is number of data, $R^2$ is the coefficient of determination, S.E. is the standard error of regression coefficient [$^\circ$C] and p is the significant probability of regression coefficient. The relationship between indoor and outdoor air temperature was not very well correlated in CL and HT modes. The reason is that the indoor air temperature were more or less controlled toward the target value of air conditioning unit. From this, we have to keep in mind that the variation of outdoor air temperature does not necessarily relay a primary role in modelling the occupant behaviour to be explained by outdoor air temperature.

3.2. Occupant Behaviour

Figure 4 shows the proportion of cooling, heating, fan use and window opening in each month. The heating was often used in winter. In spring, the proportion of heating use decreases and the proportion of window opening increases. In summer, the proportion of either cooling or fan use increases, and also, the window tends to be kept open. In autumn, the proportions of cooling and fan use decreases, and the proportion of window opening also decreases gradually. Then, the proportion of heating use starts to emerge.
The trend of fan use was similar to that of cooling use. Both fan and cooling use reach the respective maximum in August. However, when the fan use starts was earlier than when cooling use starts. We thought that the residents took the window opening behaviour alone first because of the effect of natural ventilation is sufficient from late spring to early summer. However, if the residents feel it not enough, then, they took the behaviour of controlling the air temperature by air conditioner. In such a case, the air movement by window opening is lower than the fan use. From these, we thought that the residents have 3 steps classified with the effect of cooling: first is the moderate natural air movement by window opening, second is artificial high air movement by fan use and third is the control of indoor air temperature by mechanical cooling.

Generally, the residents do not open the window during the air-conditioner are operated for energy saving. However, we thought that the residents may use the fan not only during window opening but also during cooling use. In Figure 4, it does not show the combination of fan use and window opening or cooling use. In next section, we will clarify the state of these combinations.

Figure 4 Mean proportion of the window opening and cooling, heating and fan use in each month

3.3. The Stochastic Model of Fan Use

Figure 5 shows the relationship between the proportion of fan use and outdoor air temperature. We obtained the following equation.

\[ \text{logit}(P_F) = 0.222T_e + 6.9 \]  
\[ (n=34007, R^2=0.189, \text{S.E.}=0.004, p<0.001) \]  

Figure 5 Relation between proportion of fan use and outdoor air temperature
where \( P_f \) is the proportion of fan use. When the outdoor air temperature increases, the proportion of fan use also increases. When the outdoor air temperature become 28.0°C, which is in August, the proportion of fan use is 0.335. This value implicitly indicates that fan use is common behaviour in Japanese dwellings.

3.4. Combination Model of the Fan and other Behaviours

3.4.1. The Hypothesis of Regression Curve as the Single and the Combined Model

The trend of combined use of window opening, cooling use and fan use to be a function of air temperature has not yet been found in previous studies. Therefore, we have to hypothesize its the general characteristic before analysis. Figure 6 shows the hypothesis of regression curves as fan use explained by outdoor air temperature. “Fan single use” and “fan and window opening” are represented by the curves like Gaussian function. Because there may be the transition from window opening to cooling use in the case of high outdoor air temperature. The proportion of “fan and cooling use” may be increased gradually. In the hypothesis, we assume that if the outdoor air temperature is extremely high, this proportion must become infinitely closer to 100% (It means that all the residents will use the fan and the cooling).

We don’t know maximum point of “fan single use” and “fan and window opening”. Therefore, we can not decide at which value of outdoor air temperature when these proportions reached the maximum values.

![Figure 6 The hypothesis model for single and combined fan use explained by outdoor air temperature](image)

3.4.2. The Plot of Observed Proportion for Single and Combined Fan Use

We have to examine the observed data for regression analysis. Figure 7 shows the proportion of occupant behaviour observed. These proportions were calculated for each bin of temperature interval of 1°C. The proportions of the combined or single fan use increase when the outdoor air temperature increases, and they have the saturated proportion in each cases. The proportion of fan single use, for example, have the saturation at the value of about 0.05. The proportion of combined fan use with cooling use is higher than the others. This may be related to the resident’s preference of air conditioner. This trend is different from the hypothesis model. In the future, we need to take the preference of air conditioner into consideration.

The proportion of single fan use and the combined use with window opening started to emerge when the outdoor air temperature is about 17°C. On the other hand, the proportion of the combined fan use with the cooling use start to emerge when the outdoor air temperature is about 21°C. The temperature difference with respect to emergence is about 4°C. These trends is consistant with the hypothesis model.

From this, we selected the logistic regression equation for these regression curves. The proportion of the single fan use and the combined fan use have the stable saturating trend. The maximum proportion were 0.064 for single fan use when the outdoor air temperature was 33°C, 0.256 for combined fan use
with window opening when the outdoor air temperature was 33°C and 0.156 for combined fan use with cooling use when the outdoor air temperature was 32°C. We modified the logistic regression equation based on these saturated proportions.

Figure 7 Observed proportion of single or combined fan use in 1 °C bin of outdoor air temperature

3.4.3. The Regression Equation for Single and Combined Fan Use

We conducted the regression analysis referring to the observed proportion in the previous section. Figure 8 shows the relationship between the proportion of single and combined fan use and outdoor air temperature as the observed plots together with regression lines.

The logistic regression equations obtained are as follows:

- **Fan single use**
  \[ P_{SF} = 0.064P_{cSF} \]
  \[ \text{logit}(P_{cSF}) = 0.292T_{o} + 6.3 \]

- **Combined fan use with window opening**
  \[ P_{FW} = 0.256P_{cFW} \]
  \[ \text{logit}(P_{cFW}) = 0.389T_{o} + 9.7 \]

- **Combined fan use with cooling use**
  \[ P_{FC} = 0.157P_{cFC} \]
  \[ \text{logit}(P_{cFC}) = 0.396T_{o} + 10.7 \]

where \( P_{SF} \) is the proportion of the single fan use, \( P_{cSF} \) is the corrected proportion as single fan use, \( P_{FW} \) is the proportion of combined fan use with window opening, \( P_{cFW} \) is the corrected proportion as combined fan use with window opening, \( P_{FC} \) is the combined fan use with cooling use and \( P_{cFC} \) is the corrected proportion as combined fan use with cooling use.

Figure 8 The regression models of single or combined fan use explained by outdoor air temperature
The proportion of combined fan use with window opening was higher than that with cooling use. When the outdoor air temperature is 28.6°C in August, the $P_{SF}$, $P_{FW}$ and $P_{FC}$ were 0.055, 0.212 and 0.102, respectively. The proportion of combined fan use was about twice or more higher than that of single fan use. It implies that the residents often use the combined fan use in summer.

4. Conclusions
In this study, we conducted the occupant behaviour survey and developed a set of stochastic models of single or combined fan use to has explained by outdoor air temperature. The proportions of single or combined fan use increase when outdoor air temperature increase. The combined fan use with window opening was higher than with cooling use. The opportunity of fan single use was much lower than combined fan use in the analysed period. When the outdoor air temperature is 28.6°C in August, the proportion of fan single use was 0.055, combined fan use with window opening was 0.212 and combined fan use with cooling use was 0.102. The results showed that the residents in Kanto dwellings often use the combined fan use for thermal comfort.

Acknowledgement
This study was supported by Grant-in-Aid for Scientific Research (C) Number 24560726 and (B) Number 25289200.

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