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A generalized probabilistic formula relating occupant behavior to environmental conditions

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ABSTRACT

The occupant behavior (use of heating, use of air conditioning, use of light, opening of windows, adjustment of curtains and blinds, etc.) in a building is usually closely related to the environmental conditions. This paper presents a novel general mathematical formula for describing the relationships between such behavior and the environmental conditions based on a memoryless hypothesis and psychophysical function (Stevens' power law). Compared to existing formulas, the proposed formula is simple and harmonizes both the threshold and stochastic characteristics of an occupant's response to environmental stimuli. Preliminary test showed that the formula has good applicability and reliability. The proposed formula can serve as a basic reference for detailed modeling of an occupant's heating, air conditioning, lighting, window opening, and shading adjustment behavior in the future.

1. Introduction

Heating, air conditioning, and lighting constitute a high proportion of the total energy consumption of a building and are significantly influenced by the occupants' use or adjustment of heaters, air conditioners, lights, windows, and shading devices [1]. Many efforts have been made to establish models for such occupant behavior to quantify the impact on building energy use and improve the prediction accuracy of building energy simulation programs [2–14].

Such behavior has one thing in common: a close relation to the environmental conditions [2,15–19]. For instance, a building occupant is likely to turn on a heater when a room feels cold, turn on an air conditioner when a room feels hot, turn on lighting when a room is dark, open windows when a room is stuffy, close blinds/curtains to block glare or sunlight, and so forth. In short, occupants take action to achieve and maintain their comfort if the environmental conditions in a room are outside their comfort zone [3,4,20]. The observed phenomena have prompted a practical approach to the formulation of occupant behavioral models, i.e., seeking quantitative correlations that relate occupant manipulations to environmental stimuli (e.g., temperature, illuminance, solar intensity, and CO_2 concentration) [21–23]. Based on these correlations, occupant behavior can be predicted for given environmental conditions.

A basic question is determining which mathematical formula is best suited to describing the relationship between the occupant behavior and environmental conditions. There are two main types of formulas for this purpose. One type is called "threshold formulas." According to this type of behavioral model, an occupant will definitely take action if the related environmental condition exceeds a certain critical value (i.e., threshold). Because models of this type are simple and intuitive, they have been widely used in building simulation programs [24,25]. Newsham [26], Reinhart and Voss [27], and Reinhart [28] used a fixed threshold for the sunlight intensity to predict manual control of window blinds. Newsham [26] used a fixed threshold of daylight illuminance to predict manual control of electric lighting. Jian and Jiang [29] and Zhu et al. [30] analyzed survey results to develop a model to predict when the occupants of a room will switch on a room air conditioner for cooling or heating based on whether the indoor temperature is beyond the maximum or minimum tolerance temperature. Page [31] developed a model for window opening behavior as a function of the indoor pollution and indoor temperature. In this model, the pollution concentration and temperature thresholds that determine when windows are opened or closed are stochastic (normally distributed).

The second type of model is called "regression formulas." For

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this type, the probability of an occupant's action taking place is expressed as a function of the parameters of the environmental stimulus, and the action is randomly performed with a calculated probability. The regression formula can be linear or logit in form; both are commonly used model forms in statistical regression analysis. As an alternative to threshold models, regression models cover almost all environment-related occupant behaviors. Hunt [2,32], Reinhart and Voss [27], and Reinhart [28] used logit formulas to relate the light switch-on probability to working plane illuminance. Foster and Oreszczyn [33], Sutter et al. [34], and Haldi and Robinson [17] explored the correlation of the shading adjustment to the indoor illuminance, window luminance, and other factors. Tanimoto and Hagishima [35] and Schweiker and Shukuya [36] investigated how the air-conditioning-unit (AC) operation habits of building occupants are related to indoor and outdoor temperatures. Numerous researchers [5,15,20,23,37–42] have analyzed and evaluated the influence of indoor environmental parameters (e.g., temperature, CO_2 concentration) and outdoor climatic parameters (e.g., temperature, humidity, wind, and rainfall) on window opening and closing behavior by using linear or logit regression.

Table 1 summarizes and illustrates the existing formulas for a single environmental factor, where P is the probability of success (e.g., the probability of a light being switched on); x is the predictor variable (e.g., working plane illuminance); u,a, and b are the threshold value and linear or logit regression coefficients, respectively; and the threshold formula is expressed as a step function in terms of probability (from 0 to 1 or from 1 to 0).

Both threshold and regression formulas have advantages and disadvantages in terms of their ability to describe environment-related occupant behaviors. The main advantage of threshold formulas is that their description of threshold phenomena is supported by theories of human physiology and environmental comfort [43]. Their main disadvantages are their deterministic nature and inability to reflect the inherently probabilistic nature of occupant behavior [8,24]. The main advantage of regression formulas is that they reflect a stochastic and gradually changing – rather than a deterministic and suddenly changing – relationship to environmental conditions, which is more realistic and accurate than threshold models [5,15,41]. However, they are simply observation-based statistical correlations [8,14] and thus do not formally incorporate absolute threshold characteristics.

In this paper, we propose a new general mathematical formula to predict occupant behavior by combining the strengths of the above two modeling approaches. The proposed formula is based on a memoryless hypothesis and psychophysical function. It aims to represent both the threshold and stochastic characteristics of building occupants' responses to environmental stimuli. In the remainder of this paper, we derivate the formula for relating an occupant's action in response to a single environmental factor, the results of a case study to validate the formula's applicability and reliability, and how to adapt the formula to different time intervals, multiple environmental factors, and event-related actions.

2. Modeling an occupant's action in response to a single environmental factor

According to Clarke et al. [4] and Borgeson and Brager [6], a general probabilistic model for relating an occupant's action in response to a single environmental factor (if such a relationship does exist) can be expressed as follows:

$$P\{A\} = F(x) \quad (1)$$

where A = the occupant's action, x = the environmental factor, P = the probability of the action taking place, and F = the functional formula relating x to $P\{A\}$.

Strictly speaking, however, Eq. (1) is not mathematically applicable to dynamic environmental conditions and the dynamic simulation of occupant behavior. As explained in previous studies [20,22,41], this limitation can be overcome by rewriting Eq. (1) as follows:

$$P_\tau\{A\} = F(x_\tau) \quad (2)$$

where the probability of the occupant's action at time τ, $P_\tau\{A\}$, is a function of the value of the environmental parameter x_τ at time τ. An explicit statement of a “memoryless hypothesis” is required as the mathematical basis for adopting Eq. (2) to predict an occupant's action. Such a statement has been implicit rather than explicit in most previous studies. The hypothesis can be represented in terms of the conditional probability as follows:

$$\mathbf{P}\{A_\tau | x_\tau, x_{\tau-1}, x_{\tau-2}, \cdots\} = \mathbf{P}\{A_\tau | x_\tau\} = P_\tau\{A\} \quad (3)$$

According to this hypothesis, the probability of an occupant's action at any time $P_\tau\{A\}$ depends only upon the present environmental state x_τ and not upon the sequence of past states $x_{\tau-1}$,$x_{\tau-2}$,$\cdots$. This memoryless hypothesis is vital. Based on this hypothesis and a psychophysical function, a new simple formula F can be derived and applied to both steady-state and dynamic environmental conditions.

2.1. Basic restrictions on F

For an occupant's actions stimulated by the environment, the following observations can be made on the basis of everyday experience and previous studies:

1. When an occupant stays in a comfortable environment, no action takes place [6]. Only when the environmental conditions exceed the limits of the occupant's comfort zone (i.e., higher or lower than critical levels) and produce detectable stimuli to the human body, actions take place such as turning on the AC when a room feels hot or turning on lights when a room feels dark.
2. The further the environmental conditions deviate from the limits of the occupant's comfort zone, the greater the stimulus is to the human body, the stronger the occupant's tendency is to make the room more comfortable, and the higher the likelihood is that the occupant takes action, e.g., turning on the AC or light.
3. Environmental parameters (e.g., indoor temperature, indoor illuminance) are continuous in nature; thus, their influence on the human body is cumulative and incremental. For example, the likelihood of an occupant turning on the AC gradually increases as the indoor temperature increases, and the possibility of the occupant turning on a light gradually decreases as the indoor illuminance increases.

To represent the above facts, the concrete form of F in Eqs. (1) and (2) should have the following properties:

0. Bounded: $\forall x, 0 \le P \le 1$; this is required for *probability*.
1. Threshold: $P > 0$ if and only if $x > u$ or $x < u$ (where u is the upper or lower limit of the comfort zone).
2. Monotonic: $\forall P > 0$, F is either monotonically increasing, i.e., $x\uparrow, P\uparrow$ (e.g., turn on the AC) or monotonically decreasing, i.e., $x\uparrow, P\downarrow$ (e.g., turn on the light).
3. Continuous: F is continuous for all values of x, i.e., $\forall x, \Delta x \to 0, \Delta P \to 0$.