Randomness of occupants' presences for building energy simulation

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ABSTRACT

Occupant behavior is regarded as one of the major factors contributing to the performance gap between simulation prediction and real energy use. Over the past several decades, in simulation tools, occupants have been represented as static. However, this approach of the assumption of static occupants cannot account for the dynamic behavior of occupants. Recently, many occupant models have been developed based on observed data. Such occupant models are formulated in a probabilistic fashion, e.g. discrete Markov Chain or agent-based Markov Chain.

This paper reports new evidence suggesting that occupants' presences follow a random walk pattern. The occupants' presences in two university laboratories and three university library rooms were monitored. The assumption of the random walk pattern was tested using the Normalized Cumulative Periodogram (NCP) method. It can be concluded that in certain types of buildings, occupants' presences should be treated as a random walk pattern rather than being modeled in the stochastic fashion.

KEYWORDS

Occupant presence, Occupant behavior, Performance gap, Random walk

INTRODUCTION

Recently, the study of occupant behavior has attracted significant attention from the Building Performance Simulation (BPS) community with respect to the performance gap between energy simulation and real energy use. It has been widely acknowledged that the occupant is one of the major factors contributing to this gap (Annex 66, 2016). Most of the occupants' studies have been conducted based on the Markov chain, which is based on the premise that a future state can be predicted by the present state together with the probabilities of an event occurring. However, it is crucial to verify whether or not occupant behavior models can be developed in a stochastic manner. If the characteristics of occupants' presences are not stochastic but rather similar to a random walk pattern, then it would be impossible to predict the occupants' presences. The random walk is a mathematical formalization of a path that consists of a succession of random steps. In the view point of random walk, the aforementioned stochastic models

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(e.g. Markov chain models) cannot be applicable to the buildings in which occupants exhibit 'random walk' behavior.

In this context, this study investigates the predictability of occupants' presences in two laboratories of S University and three library rooms of K University. The five spaces were purposefully selected since the authors assumed that university laboratories and library rooms have workspace environments similar to offices but that the occupants' presences in the five spaces might differ sufficiently. The authors gathered occupants' presences data of the five spaces using a series of experiments. Then, Normalized Cumulative Periodogram (NCP) was used to verify the degree of randomness of occupants' presences in the five spaces.

RANDOM WALK

A random walk is a mathematical formalization of a path that consists of a succession of random steps. The mathematical form of random walk for time-series data is as follows (Gelb 1974):

$$x_{k+1} = x_k + w_k \quad (1)$$

$$w_k = x_{k+1} - x_k \quad (2)$$

where x_k is the state of the kth time-step, x_{k+1} is the state of the (k+1)th time-step, and w_k is the difference between x_k and x_{k+1}, meaning the difference in the state over time. w_k can be used to examine the periodic behavior. The Normalized Cumulated Periodogram (NCP) is a common method for identifying the periodicity of a given time-series in a frequency domain (Hipel and McLeod 1994).

The randomness of w_k can be identified if the power spectrum density of w_k is evenly distributed over the frequency in the NCP. The time-series data of randomness is not concentrated in the few specific frequencies, but is uniformly distributed within the entire frequency domain. Therefore, it can be said that w_k follows the random walk if it is drawn within a confidence interval along with a straight line joining (0, 0) and (0.5, 1) in the NCP (Hipel and McLeod 1994).

EXPERIMENTS

The occupants' presences in two laboratories at S University and three reading rooms at K University (Figure 1) were monitored as shown in Table 1. The arrival time and departure time of the occupants were recorded using webcams. Based on the recorded scenes, the occupants' presences were calculated at a sampling time of 10 minutes (Case A) and 1 minute (Cases B, C, D, E, and F) (Table 1). The different sampling times were applied, since the purpose of the Case A experiment was originally to study the cognitive responses of occupants and Cases B to F were conducted to investigate the predictability of the occupants' presences.

Table 1. *Overview of six experiments*

Experiment	*Name and use of space*	*Max. number of occupants*	*Measurement period and dates*	*Sampling time*

			during experiments		
A	Laboratories in S University	U-lab.	8	1 day (Tue.) June 20th	10 min.
B		BS-lab.	5	1 day (Tue.) Feb 26th	1 min.
C		BS-lab.	7	4days (Mon. to Thu.) Mar 2nd-5th	1 min.
D	Reading rooms in K University	Room#1	31	1day (Mon.) Oct 22th	1 min.
E		Room#2	9	1day (Mon.) Oct 22th	1 min.
F		Room#3	15	1day (Mon.) Oct 22th	1 min.

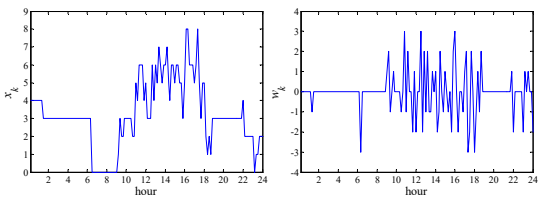
(a) U-laboratory at S University

(b) BS-laboratory at S University

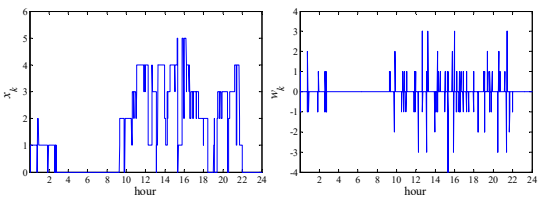
(c) Three reading rooms at K University

***Figure 1**. Photos of laboratories and rooms*

In the cases of Experiments A, B, and C (Table 1), there were no fixed/strict office hours. Graduate students were able to enter and leave the labs according to their own preferred schedules. In the cases of the library reading rooms (Experiments D, E, and F, Table 1), the library opens at 8:30 A.M. and closes at 11:00 P.M.



(a) Experiment A



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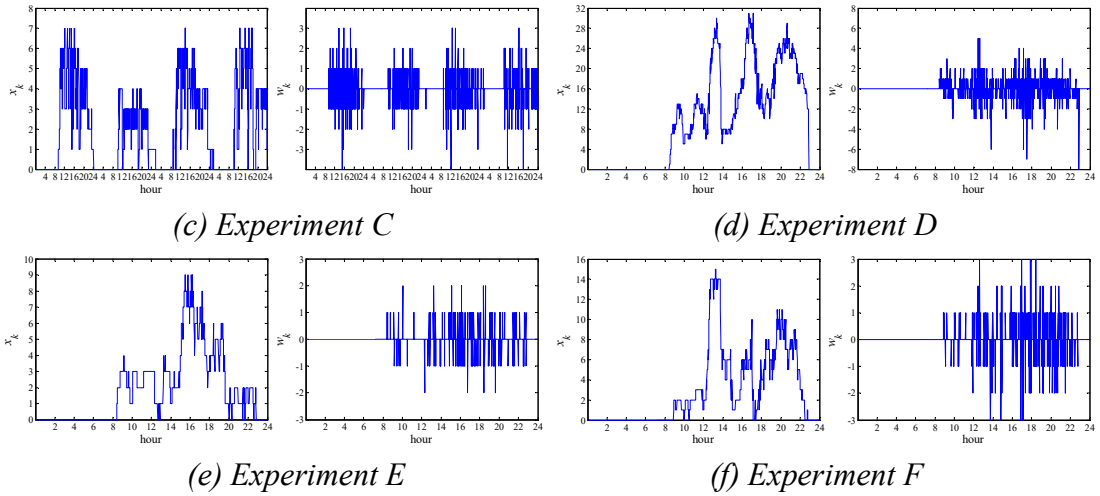


(c) Experiment C *(d) Experiment D*

(e) Experiment E *(f) Experiment F*

***Figure 2**. Occupants' presences (x_k, left) and variation in occupants' presences (w_k, right)*

RESULTS

To verify whether or not the occupants' presences follow the random walk, the occupants' presences (x_k) (Equation 1) and variation in occupants' presences (w_k) (Equation 2) were tested by the NCP. Table 2 shows the period converted from the frequency in the NCP plot for the sake of clarity (Figure 3, Table2). Due to this replacement, the period on the X axis is in descending order since the period is an inverse of frequency.

As shown in the Figure 3 and Table 2, the NCP of the occupants' presences sharply increases in the range of the periods between 1,440 min and 144 min. For example, 82%, 75%, 85%, 93%, 88% and 89% of the periodicities for the occupants' presence (x_k) in the Experiment A, B, C, D, E and F, respectively.

Interestingly, the NCPs of the variation in occupants' presences (w_k) in the Experiment A (Figure 3(a)), B (Figure 3(b)), D (Figure 3(d)), E (Figure 3(e)) and F (Figure 3(f)) are located inside the 95% confidence limit. This means that the spectral density of w_k is evenly distributed over all the periods (or over the entire frequencies). Thus, each w_k of the experiments are unpredictable and follows the random walk. In other words, the occupants' presences at the next time step cannot be predicted since each w_k is unpredictable.

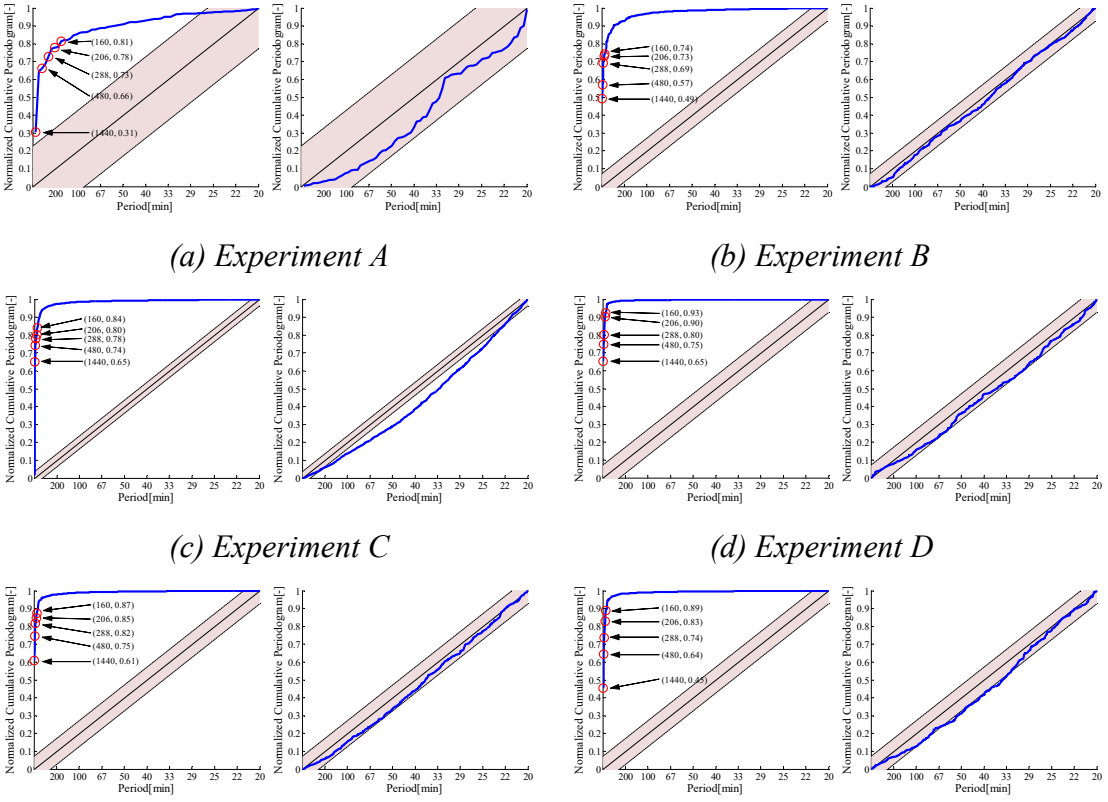
However, the spectra of w_k (right side of Figure 3(c)) are located slightly outside of the lower dotted line. It can be said that the occupants' presences (x_k) of experiment C *marginally* follow a random walk, since the degree of the deviation from the confidence interval is not significant.

***Table 2.** NCP of occupants' presences (x_k)*

Index	Period (min)	Period (hours)	Exp. A NCP (-)	Exp. B NCP (-)	Exp. C NCP (-)	Exp. D NCP (-)	Exp. E NCP (-)	Exp. F NCP (-)
1	1,440	24.0	0.31	0.49	0.65	0.65	0.61	0.45
2	720	12.0	0.64	0.55	0.70	0.70	0.67	0.46
3	480	8.00	0.66	0.57	0.74	0.75	0.75	0.64
4	360	6.00	0.69	0.58	0.76	0.77	0.81	0.73
5	288	4.80	0.73	0.69	0.78	0.80	0.82	0.74
6	240	4.00	0.77	0.71	0.79	0.87	0.82	0.79

7	206	3.43	0.78	0.73	0.80	0.90	0.85	0.83
8	180	3.00	0.78	0.74	0.83	0.92	0.86	0.86
9	160	2.67	0.81	0.74	0.84	0.93	0.87	0.89
10	144	2.40	0.82	0.75	0.85	0.93	0.88	0.89

* Red circles in Figure 3 correspond to indices #1, 3, 5, 7, and 9.



(a) Experiment A *(b) Experiment B*

(c) Experiment C *(d) Experiment D*

(e) Experiment E *(f) Experiment F*

***Figure 3**. NCP of occupants' presences (x_k, left) and variation in occupants' presences (w_k, right)*

DISCUSSION

The results of the six experiments confirm the evidence of the random walk. This output is contradictory to the prediction of occupants' presences by the Markov chain model. Figure 4 demonstrates the aim of this paper. The X axis represents the degree of randomness, or predictability, in the occupants' presences. Process-driven buildings such as K-12 school buildings, offices, factories, etc. are located at the far left on the X axis, in which high stochastic predictability inheres. In contrast, in a number of other building types, the occupants' presences in the university labs and reading rooms follow the random walk in this paper. Obviously, any stochastic model can fail to predict the occupants' presences in random walk driven buildings. Therefore, more studies need to be carried out to characterize building types and develop a new prediction model for random walk-driven buildings.

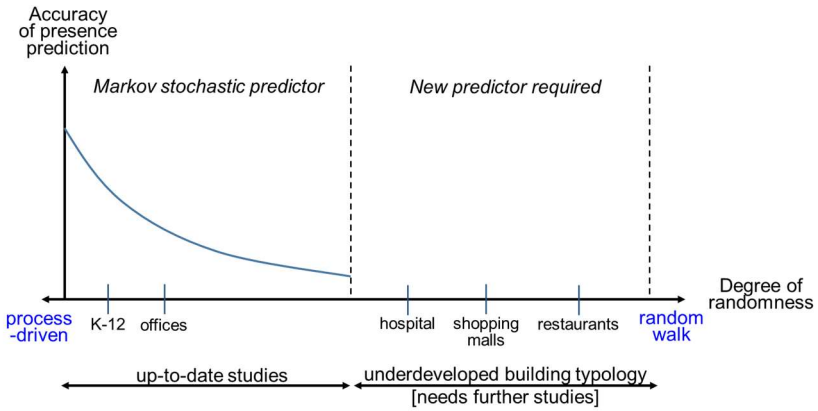


***Figure 4**. Predictability of occupants' presences according to building types (the location of building types on X axis can vary)*

CONCLUSION

The aim of this study is to deliver a new finding on occupants' presences based on the so-called random walk pattern. A series of experiments was conducted to obtain the occupancy data in two laboratories and three reading rooms at two different universities. The degrees of randomness of the occupants' presences in the five spaces were verified using the NCP. The results show strong evidence of the random walk pattern with regard to the occupants' presences. This means that it is difficult to predict the variation in the number of people over a certain time interval.

This study presents a new concept, 'random walk' occupants' presences. However, it should be noted that this study was performed in two laboratories and three reading rooms at two universities; such buildings significantly differ from process-driven buildings such as K-12 schools, factories, etc. Accordingly, more work on occupants' presences needs to be performed considering the characteristics of buildings.

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