Applied Energy 173 (2016) 272–282

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An empirically grounded model for simulating normative energy use feedback interventions

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HIGHLIGHTS

- An empirically grounded behavior model for normative energy feedback interventions.
- Only sending normative feedback to individuals above the mean energy works.
- This alternative technique can be easily applied on a large scale with little cost.

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 7 March 2016
Accepted 10 April 2016
Available online 16 April 2016

Keywords:
Agent-based modeling
Normative feedback
Residential energy use
Occupant behavior
Behavior diffusion

ABSTRACT

Researchers have begun developing simulation models as a cost-effective and expeditious means to explore and enhance our understanding of energy use behavior interventions. These models have provided unique insights into potential energy savings as a result of improved occupant behavior, but have not yet reached the capability to be used for predictive modeling purposes. Therefore, this paper attempts to build on previous modeling efforts and develops an empirically and conceptually grounded occupant behavior model for simulating normative feedback interventions based on literature from the social science and field data. This model is then used to conduct "what if" analyses testing three novel normative feedback intervention strategies and the effect of social network structure on intervention outcomes. The most successful and immediately applicable strategy consists of sending normative feedback only to individuals who use more energy than the group norm. This strategy resulted in a mean energy use reduction of 1.4 kW h per week per occupant, 2.2%, relative to traditional individual and normative feedback strategies used today. Lastly, it was found that the social network structure in which the interventions took place affected the absolute outcomes (i.e., net change) of the simulations but not the relative outcomes (i.e., strategy ranking).

1. Introduction

Currently in developed countries buildings consume around two-fifths of all energy and are responsible for an equal proportion of carbon emissions [1–3]. Within buildings, specifically residential buildings, occupant behavior can have a significant impact on energy consumption [4–8]. Given the importance of reducing anthropogenic emissions numerous efforts and studies have attempted various behavior interventions to improve occupant energy use behavior [9–11].

Energy use behavior interventions have been developed based on a variety of theoretical behavior models; some of the more prominent theoretical models include the education-based models [12,13], rational actor models [14], and norm-based models [15,16]. Energy use interventions have employed a wide spectrum of techniques including the use of prompts, justification, declarative information, rewards, social modeling, cognitive dissonance, gaming, commitment, goal setting, and feedback [10,17]. Of these approaches energy use feedback has received the most attention to date and continues to gaining more interest from researchers, utility companies, and other stakeholders as energy monitoring and reporting capabilities continue to improve with advances in technology.

Energy use feedback can be presented in a number of different forms and through a variety of mediums such as SMS messaging, email, paper, and home energy management systems [18–20]. The mode that feedback is presented can affect the effectiveness of the feedback [21]. In its simplest form a consumer can receive their individual energy use feedback, that is, information as to how much energy they consumed over a given period, e.g., "last billing cycle you used 100 kWh". Periods can be as long as billing

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http://dx.doi.org/10.1016/j.apenergy.2016.04.063
0306-2619/

cycles or available in near real time [22]. The longer the delay between behavior and feedback the less effective the feedback tends to be [9]. Consumers can also receive comparative, or normative, feedback. Normative feedback adds information as to the behavior of a reference group, e.g., neighbors, and may add also include elements to indicate approval or disproval of current behavior, i.e., injunctive norms, as is becoming more widespread [23–27]. Comparative feedback has been found to at times induce undesirable behavior change as individuals increase their consumption to be in line with group norms. This is sometimes referred to as the boomerang effect. The addition of injunctive elements to normative messages is used as a technique to help mitigate this effect [27]. Feedback can also be displayed in alternative units or images that aim to induce an individual to reduce their environmental impact, i.e., eco-feedback [28]. In eco-feedback consumption can be translated into environmentally provocative images or express consumption in environmentally meaningful terms such as quantity of CO_2 equivalent emissions [29–31]. These messages have been found to be more effective than traditional individual feedback.

Conducting behavior intervention experiments is a natural and extremely useful means to test and validate intervention techniques. Unfortunately, field experiments can be costly and time consuming to conduct and can face barriers to implementation (e.g., privacy concerns). Therefore, researchers have begun developing simulation models as a cost-effective and expeditious means to explore and enhance our understanding of existing and novel behavior interventions [32–37], as well as diffusion of behavior and technology [38,39].

Focusing specifically on behavior intervention simulation models, models to date can be classified into one of two categories: (1) highly conceptual exploratory models that intend to provide insight into how complex factors affect intervention strategies [34–36]; or (2) models which aim to estimate the impact of changes in occupant behavior on energy consumption [32,33,37]. These models have typically been developed as agent-based models. Agent-based models are bottom-up models where heterogeneous agents interact amongst each other and follow various behavior rules [40]. Agent-based modeling is an appropriate modeling tool for this branch of research for several reasons. First, agent-based modeling allows researchers to accurately represent the heterogeneous nature of building occupants. Not all building occupants are the same or equally influenced interventions or their environment. Second, agent-based modeling allows for agents, or occupants, to be adaptive and learn from their environment and others which is the basis for the diffusion of behavior. Third, agent-based modeling is highly flexible and permits the construction of complex social networks over which information and behavior and be diffused. The models made to date have provided unique insights into potential energy savings as a result of improved occupant behavior and how complex factors can affect intervention success, but have not yet reached the capability to be used for predictive modeling purposes.

According to Axtell and Epstein [41], the performance of an agent-based model can be assessed and categorized by how accurately it represents reality. Axtell and Epstein [41]'s classification focuses on accurately, both qualitatively and quantitatively, reflecting both macro level structures (e.g., group level behavior) and micro level structures (e.g., individual occupant behavior). They developed tiers of modeling performance which build upon each of the previous as follows. The lowest level of modeling performance and accuracy is present when the agent behavior rules are in qualitative agreement with the micro behavior. The second tier is achieved when the model's behavior is in qualitative agreement with empirical macro structures. The third tier is achieved when the model's behavior is in quantitative agreement with empirical macro level structures. Lastly, the highest level of modeling performance is achieved when the model's behavior exhibits quantitative agreement with micro level structures.

In the previous studies most models have only achieved the first tier of performance—model performance is in qualitative agreement with micro level structures. If these behavior models are to be used for predictive modeling purposes and "what if" scenario analysis it is crucial that higher performance models are developed which are grounded in sound conceptual theories on human behavior as well as empirical data. Therefore, this paper develops a novel empirically refined and conceptually grounded occupant behavior model for simulating normative feedback interventions based on established theories from the social science literature and experimental findings. This model aims to be capable of qualitatively and quantitatively exhibiting agreement in both macro- and micro-level structure behavior found in the field. This would represent a significant advancement in the state-of-the-art of modeling pro-environmental behavior interventions and would in turn permit researchers to conduct "what if" analyses testing several novel normative messaging feedback intervention strategies.

2. Methods

In this section the model is detailed using the ODD (Overview, Design concepts, Details) protocol for describing agent-based models [42,43]. This protocol is applied to help improve the clarity, completeness and reproducibility of the model. The model has been programmed in Java using Repast J v 3.0 [44].

2.1. Purpose

The model detailed below has been developed to provide a means to test new and alterative normative feedback intervention strategies attempting to reduce household energy consumption. During normative behavior interventions, behavior can spread from one participant to another. As a result, the structure of social ties in the community where the intervention is taking place, i.e., the social network, can influence the outcome of the intervention [35,36]. Knowledge as to the social network structure in residential communities is currently limited so this model also investigates how interventions are affected by two different probable social network structures: block configuration networks (BCN) [45] and small world networks (SWN) [46]. In the literature other social network structures have been considered such as scale-free or preferential attachment, networks and random graphs. These two network structures are not considered in this research. Scale-free networks feature power-law distributions and have been found to represent such things as paper citation networks and the internet [47]. However, scale-free networks are unlikely to be representative of social networks in residential communities due to the limited capability for humans to maintain such potentially vast quantities of relationships as would be required by this network topology. In addition to scale-free networks random graphs have been considered to explain the social networks of residential communities, but are also not considered in this paper [48]. Random graphs are not believed to be representative of social networks in residential communities. Conceptually a random graph of the residential community of a city asserts that one is equally likely to know their next door neighbor as they are a person on living on the other side of town.

2.2. Entities, state variables, and scales

The agents in this model are the building occupants. Each building occupant has multiple attributes. Every building occupant is