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Simulating the human-building interaction: Development and validation of an agent-based model of office occupant behaviors

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A R T I C L E I N F O

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A B S T R A C T

This paper develops and validates an agent-based model (ABM) of occupant behavior using data from a one-year field study in a medium-sized, air-conditioned office building. The full ABM is presented in detail using a standard protocol for describing this type of model. Simulated occupant "agents" in the full ABM behave according to Perceptual Control Theory, taking the most immediate, unconstrained adaptive behaviors as needed to maintain their current thermal sensation within a reference range of seasonally acceptable sensations. ABM validation assigns simulated agents the personal characteristics and environmental context of real office occupants in the field study; executes the model; and compares the model's ability to predict observed fan, heater, and window use to the predictive abilities of several other behavior modeling options. The predictive performance of the full ABM compares favorably to that of the other modeling options on both the individual and aggregate outcome levels. The full ABM also appears capable of reproducing more familiar regression relationships between behavior and the local thermal environment. The paper concludes with a discussion of the model's current limitations and possibilities for future development.

1. Introduction

Long-term field observations of building occupants broadly support Humphrey's hypothesis that *"If a change in the thermal environment occurs, such as to produce discomfort, people react in ways which tend to restore their comfort"* [1]. Indeed, occupant adaptations are seen to contribute to both thermal comfort and energy use outcomes [2,3].

To account for occupants' adaptive behaviors as part of the building design and operation processes, several behavior models have been developed over the last decade for integration with whole building energy simulations. The most prominent of these models are regression-based, describing the group-level probability of a given behavior in terms of thermal stimuli like indoor and outdoor temperature [4]. The regression-based models are commonly calibrated to data from cellular offices in naturally ventilated buildings in Europe, and focus most often on window opening.

Examples of existing regression-based models are found in the study of Nicol [4], which introduces the concept of simulating multiple behaviors stochastically using generalized linear models; the study of Rijal et al. [5], which calculates the probability of a window opening in terms of operative indoor and outdoor air temperatures after a +/-2K deadband around "comfort temperature" has been breached (the "Humphreys algorithm"), and which also suggests the incorporation of "active" and "passive" window users; the study of Yun and Steemers [6], which fits sub-models of window opening probability for occupant arrival, intermediate, and departure periods, with indoor temperature and previous window state as predictor variables; and the studies of Haldi and Robinson [7,8], in which the authors find occupant behavior to be better described by internal than external temperature, and develop sub-models for window opening probability for arrival, intermediate, and departure times using Markov chains coupled with survival analysis.

In general, the regression-based models have the advantage of being simple to communicate and implement as part of building simulation routines. However, some issues arise with their use:

- The models typically only roughly account for inter-individual variability in behavior through the definition of "active" and "passive" occupant groups.

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- The models do not simulate multiple behaviors together or address behavioral sequencing.
- The models do not account for social influences/other constraints on behavior in non-private offices.
- Few models address the most immediate adaptive opportunities (clothing, personal fans/heaters) despite the substantial use of these behaviors when available [9].
- The extensibility of these models to air-conditioned buildings in climates with greater seasonal variability is not well established.

It has recently been suggested that some of the above points could be addressed by the development of Agent-Based Models (ABMs) of occupant behavior [10]. ABMs represent individuals as autonomous "agents" with personal attributes and behavioral possibilities, as well as rules for interacting with other agents and their surrounding environment [11]; group-level behaviors then emerge from the adaptive behaviors of individual agents. In the context of building occupant behavior, ABMs continue a conceptual progression of existing modeling approaches as shown in Fig. 1.

A few existing studies have attempted to develop ABMs of building occupants' behavioral adaptations. For example, Andrews et al. [12] coupled an ABM of daily office occupant lighting use with the RADIANCE software, basing agent decisions on the Belief-Desire-Intention (BDI) software model. Azar and Menassa [13] modeled interactions between office occupant agents of different energy consumption habits as they relate to whole building energy use. Lee and Malkawi [14] used an agent-based model to explore how a single hypothetical commercial building occupant might adapt to changing thermal conditions in a manner that optimizes thermal comfort or energy savings, with five adaptations considered in the modeling approach.

In the residential context, Chen et al. [15] developed an agent-based model of individual resident energy consumption behavior to explore the effect of peer network structure on energy saving behavior in residential buildings. The authors used individual electricity consumption data collected from 45 occupants over 46 days to calibrate initial individual energy use distributions and social network weights, and found that tighter and more robust associations between network members are more important than network size in influencing energy savings behavior. Kashif et al. [16] used a daily activity survey to build an agent-based model of reactive and deliberative thermal behavior profiles for a family in France, incorporating perceptual, psychological, and social behavioral drivers in the developed model. Multiple agent-based models have also been developed to simulate residential water use [17,18].

The above studies suggest the promise of using an agent-based approach to represent individual occupants' adaptive behaviors as part of building simulation; however, the studies also reveal two consistent shortcomings:

- ABM descriptions are not presented in a standard manner that is clear and complete. Key details about the modeling assumptions, source of agent behavior rules, etc. are often missing, making it difficult for other researchers to interpret, reproduce, and build upon the given model.
- A general approach to ABM validation is not provided; the studies do not validate outputs from developed models against long-term field data on behavior.

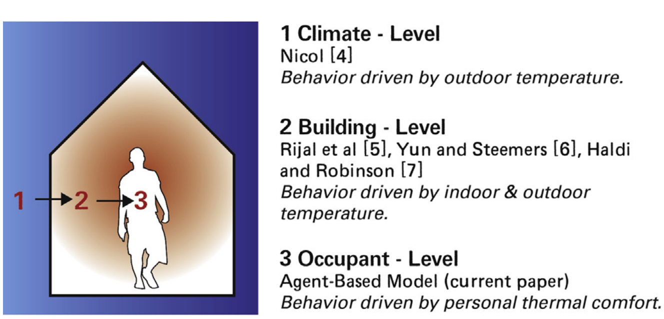

Fig. 1. Conceptual progression in behavior modeling approaches.

With these shortcomings in mind, this paper presents the development and validation of a novel ABM of thermally adaptive office occupant behavior in a way that is clear to other researchers and useful to future behavior model-building efforts. The paper builds towards two primary outcomes: 1.) A comprehensive ABM of office occupant behavior that reflects key findings on personal comfort and environmental adaptation in the field, and which is presented using a standard description protocol, and 2.) A validation of the developed ABM against long-term field data on behavior and comparison of its predictive performance to that of multiple other behavior modeling approaches.

2. Methods

2.1. Field study

Development and validation of this paper's agent-based occupant behavior model draws from longitudinal field comfort and behavior data collected by the authors [19]. Here, key aspects of the field study, conducted between July 2012 and July 2013 in the Friends Center medium-sized office building in Philadelphia, PA, are reviewed:

- **Subject sample.** From an initial sample of 45 occupants who completed a background survey that asked about personal characteristics, typical occupancy periods (arrival/departure times), general thermal comfort, and behavioral control opportunities in the office, a final sample of 24 occupants was selected for participation in the full study. The final sample includes occupants of all office types (private/semi-private/open), from all floors of the building, with varying control opportunities that include the use of windows ($N=10$) and personal heaters/fans ($N = 4$ and $N = 5$, respectively).
- **Daily surveys.** For two weeks in each season, the occupant sample completed an online survey three times daily (shortly after arrival; late morning; late afternoon). The survey included questions about recent occupancy; work flow/productivity; thermal comfort; thermal sensation, acceptability, and preference; and recent behavioral opportunities and actions. At the end of two weeks, a final retrospective survey asked about occupancy, thermal comfort, and behavior over the past two weeks of surveying.
- **Environmental measurements.** Across the full year of the study, data loggers measured the local thermal environment continuously. Local ambient temperature was logged for all occupants, either through HOBO loggers (Onset, Bourne, MA) at their desks (5 min interval) or through nearby thermostat readings (15 min interval). Relative humidity was measured at the desks of half the occupant sample (5 min); globe temperature was measured at one perimeter and core desk on each floor (5 min); and air velocity was measured at one desk on each floor (5 min).
- **Behavior measurements.** Personal fan and heater use were logged at 15-min intervals using WattsUp? power meters (EED, Denver, CO). Window use was monitored using HOBO state loggers.

The Results section summarizes field study findings with the greatest significance to behavior model development.