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Quantifying the human–building interaction: Considering the active, adaptive occupant in building performance simulation

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ABSTRACT

This paper introduces a Human and Building Interaction Toolkit (HABIT) for simulating the thermally adaptive behaviors and comfort of office occupants alongside building energy consumption. The toolkit uses the Building Controls Virtual Test Bed (BCVTB) to co-simulate a field-tested, agent-based behavior model with an EnergyPlus medium office model. The usefulness of the toolkit is demonstrated through a series of zone and building-level case study simulations that examine the wisdom of pairing local heating and cooling options with strategic thermostat set point offsets, judging from the energy, Indoor Environmental Quality (IEQ), and cost perspectives.

Results generally suggest that trading efficient local heating/cooling options for whole space conditioning has both energy and comfort benefits, saving up to 28% of monthly HVAC energy while improving the acceptability of thermal conditions in a Philadelphia climate. Nevertheless, cost analysis shows that the fuel source of conserved energy must be considered – particularly in the case of personal heater use, which adds to electric plug loads and associated utility and CO_2 emissions cost penalties. Moreover, costs from even small changes in simulated occupant productivity tend to overwhelm energy costs, suggesting the need to improve the accuracy and precision of available productivity models across multiple seasons and climates.

1. Introduction

Real office building occupants interact with and adapt to their surrounding environments in deliberate and meaningful ways that affect both energy consumption and Indoor Environmental Quality (IEQ). Numerous studies have estimated the magnitude of these effects, establishing the high degree of influence that occupant behavior exerts on building energy use and thermal comfort relative to other potentially significant factors [1–3].

Given the importance of occupants' environmental adaptations to building energy and comfort outcomes, a series of regression-based occupant behavior models have recently been integrated into building performance simulation (BPS) routines. Bourgeois [3], for example, joined a Sub-Hourly Occupant Control (SHOCC) model with the ESP-r building simulation program. The SHOCC module overrides ESP-r lighting diversity profiles at 5 min time steps with stochastically determined occupancy, blind use, and lighting behavior information for a single private office. Running the SHOCC scheme for the Quebec, Canada and Rome, Italy climates, the authors found manual versus constant lighting control reduced lighting consumption by 79% in Rome and 77% in Quebec, and also reduced cooling loads by 42% and 57% and primary energy loads by 60% and 43%.

Rijal et al. [4] modeled the probability of window opening behavior in terms of operative indoor and outdoor air temperatures once a ±2 K deadband around the group "comfort temperature" has been breached. The algorithm has been integrated into an ESP-r simulation of a single UK office at an hourly time step.

Haldi and Robinson [2] integrated stochastic, Markov-chain-based models of average occupant window and blind use into the City-Sim urban simulation software, using indoor/outdoor temperature and indoor/outdoor illuminance as inputs to the window and blind use models, respectively. The behavior models were implemented in a City-Sim simulation of a single private office at a 5 min time interval, with the energy impacts of the modeled behavior reportedly on the order of a factor of two.

While the above regression models describe the probabilities of *group-level* behaviors (i.e., total percentage of windows open in an open plan office), a few recent studies represent *individual-level* occupant behaviors in BPS via an Agent-Based Modeling (ABM) approach. An ABM represents individual building occupants as autonomous "agents" with unique personal attributes and behavior

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possibilities, as well as rules for interacting with other agents and their surrounding environment [5]; group-level behaviors then emerge from the adaptive behaviors of individuals. The natural ability for agent-based models to represent individual behavioral diversity makes them particularly attractive for a BPS application, which typically concerns building spaces with multiple occupants [6].

Previous occupant behavior ABMs include that of Azar and Menassa [7], who represent ten low, medium, and high energy consuming occupant agents and their interactions in an e-Quest model of a single graduate office at monthly time steps. The agents vary in their use of blinds, lighting/equipment use schedules, and hot water consumption. The authors found that on average, the simulations showed a 39% difference in electricity consumption and an 11% difference in gas consumption between "Low" and "High" consumers.

Another study by Andrews et al. [8] couples an ABM of occupants' daily lighting use with the RADIANCE lighting simulation software, simulating a five-zone office building at hourly time steps for one day total. The authors use the coupled simulation to determine an optimal window-to-wall ratio of 30% for the building, given the multiple objectives of minimizing visual discomfort; minimizing the number of lighting control actions; and minimizing energy use and costs.

From a review of the existing modeling work above, the following areas for improvement in behavior co-simulation for BPS have been identified:

- *Generality and scope of underlying behavior models*. It is unclear how effectively statistical behavior models can make predictions outside the context of their calibration; moreover, many of these models only roughly account for inter-individual variability in behavior through "active" and "passive" occupant groupings; do not generally address social influences on behavior in non-private offices; and rarely model the most immediate adaptive opportunities (clothing, personal fans/heaters). While agent-based behavior models are better suited to handling individual variability in comfort/behavior and social interactions, available ABMs are inconsistently reported and few have been validated against long-term field data.
- *Flexibility and performance of behavior/energy co-simulation approaches*. Most existing behavior/energy co-simulation studies simulate behavior and energy in a single thermal zone – often with one occupant – and it is unclear whether multiple building zones with several occupants could be accommodated for studies at the whole building level. Co-simulations that do represent multiple zones and/or occupants are run either across a short time period (e.g., one day) or at a coarse time step (e.g., one month) that may miss short-term behavior dynamics. Moreover, existing studies rarely report the computational time for co-simulation runs, precluding the definition of acceptable thresholds for co-simulation performance.
- *Interpretability and comprehensiveness of co-simulation outputs*. Previous studies typically report energy use changes associated with various occupant behavior scenarios; yet, the definition of "energy use" differs across studies, sometimes signifying overall energy; other times focusing on specific end uses or fuel types; and also varying between site and source energy. Output metrics like cost, which are more meaningful to those outside of the building performance modeling community, are rarely explored; nor are IEQ metrics like thermal acceptability and productivity, though their inclusion would yield a more holistic understanding of behavior impacts on building operation.

This paper introduces a Human and Building Interaction Toolkit (HABIT) that seeks to address the above issues. Specifically, the toolkit co-simulates building energy and office occupant behavior using a field-validated, agent-based model that represents both individual and group-level comfort/behavior outcomes; the co-simulation accommodates whole building-level analyses; and co-simulation outputs allow assessment of energy, behavior, IEQ, and cost together as a guide to the design and operation of low-energy, high quality office building environments.

The paper begins by describing the HABIT co-simulation exchange and its underlying agent-based model of thermally adaptive behaviors. The usefulness of the toolkit is then demonstrated through a series of zone-level and whole building-level simulations that explore a range of occupant behavior scenarios, including multiple cases where wider thermostat set point ranges are paired with the provision of efficient local heating and cooling options for occupants. The relative merits of each scenario are assessed by comparing resulting energy use intensities alongside occupant thermal unacceptability and productivity outcomes; the whole building-level simulations also assess the costs of changes in each of these outcome metrics across the various behavior scenarios.

2. Methods

2.1. Integrated modeling scheme

2.1.1. Co-simulation overview

HABIT pairs a previously published ABM of office occupants' thermal comfort and adaptive behaviors [9] in MATLAB with whole building energy simulations of office buildings in EnergyPlus [10] using the Building Controls Virtual Test Bed (BCVTB) co-simulation program [11].

The EnergyPlus/MATLAB information exchange runs as follows (see Fig. 1): EnergyPlus simulates zone-level thermal conditions and passes these as inputs to the MATLAB comfort/behavior model; the MATLAB model predicts thermal comfort and related behavior outcomes for each occupant (i.e., fan on; window open, etc.) and aggregates these outcomes across all agents in the zone; the aggregated behavior outcomes are passed back to EnergyPlus and used to adjust appropriate zone schedules (i.e., heater/fan equipment gains; thermostat set points) for the next time step; the process repeats until a simulation end time is reached.

The BCVTB negotiates single runs of the above MATLAB/EnergyPlus exchange. However, the MATLAB comfort/behavior model contains probabilistic elements (see below). Thus, the exchange must be re-run multiple times to assess a range of possible outcomes. These re-runs are achieved through a custom MATLAB wrapper that reopens and executes a given BCVTB system.xml file for as many simulation runs as the user specifies. Once all runs are completed, the R Computing software is used to aggregate results and perform uncertainty analysis. The entire co-simulation process is currently configured through a designated Excel file.

2.1.2. Agent-based behavior model overview

In the default HABIT setup, each office occupant is represented in the MATLAB comfort/behavior model as a simulated agent that acts adaptively based on the scheme described in [9], which draws upon Perceptual Control Theory (PCT) [12]. Under this scheme, behavior is considered to be the by-product of a negative feedback loop in which an agent acts to bring its current thermal perception into line with a reference range of seasonally acceptable ASHRAE thermal sensations, despite environmental disturbances. This process is diagrammed in Fig. 2.

An agent's current thermal sensation and seasonally acceptable thermal sensation range are both modeled probabilistically using the distributions developed in [13]; daily occupant