AN OCCUPANCY-DRIVEN FRAMEWORK TO OPTIMIZE ENERGY CONSUMPTION AND HUMAN COMFORT IN A GROUP OF BUILDINGS

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ABSTRACT

A core principle of sustainable building performance is to provide comfortable living and working environment for occupants while at the same time prevent high energy consumption levels. Therefore, increasing sustainability in an individual or group of buildings requires an integrated approach, to ensure that energy conservation efforts do not compromise human comfort and well-being, and vice-versa. This study presents a conceptual Agent-Based Modeling (ABM) framework that integrates human attributes and characteristics in the performance evaluation of a group of buildings. The framework serves as a proof-of-concept for the multi-disciplinary approach needed to capture the various dimensions of sustainable building performance. Additionally, an example is used to illustrate how the model can capture the trade-off between energy consumption and thermal comfort for a group of buildings.

INTRODUCTION

Residential and commercial buildings account for a large share of the world's total end use of energy. According to the International Energy Agency (IEA), this share is around 35 percent for the member states of the Organization for Economic Co-operation and Development (OECD), and 40 percent globally (IEA 2008). Reducing the energy intensity of the building sector can therefore greatly contribute to large-scale reductions in energy consumption and carbon emissions. This has motivated extensive research in literature to evaluate various drivers of building energy use and investigate energy saving strategies.

The majority of studies typically focus on improvements in building design and technology (e.g., retrofits) (Afshari et al., 2014; Chidiac et al., 2011), as well as improvements in human control and operation strategies (e.g., adjusting thermostat temperatures to conserve energy) (Langevin et al., 2014; Azar and Menassa, 2012b; Barooah, 2011).

In parallel, buildings can have a significant impact on people's health and well-being. According to the Environmental Protection Agency (EPA), it is estimated that an average person can spend up to 90 percent of his/her life indoors (EPA, 2009). Consequently, a large number of studies focus on assessing and improving people thermal comfort, as it has shown to also affect well-being and productivity (EPA, 2012; Nicol and Humphreys, 2002).

In recent years, researchers have been broadening their focus from individual buildings to neighborhoods or cities (Rakha et al., 2014). The observed shift towards a macro evaluation of the built environment introduces new variables and metrics specific to groups of buildings. Examples include occupancy schedules and movement between buildings, outdoor thermal conditions, and walkability factors.

All of the above-mentioned studies on energy consumption, thermal comfort, and human movement and interactions, overlap and are essential to evaluate building performance in a comprehensive manner. However, despite their interdependence, they remain in most cases disaggregated. In particular, there is lack of multi-disciplinary efforts to integrate these studies and better understand the implications they can have on each other. As a result, many important questions remain unanswered.

For instance, despite the strong trade-off that exists between energy consumption and thermal comfort, the majority of studies on energy conservation measures in buildings overlook potential implications on human comfort. Thus, a challenge is rising for researchers to find ways to moderate energy consumption while maintaining a balance in this trade-off. As another example, despite the growing interest in green cities and communities, it is currently unclear how occupancy movement between buildings affects performance metrics such as energy consumption levels as well as indoor and outdoor thermal comfort levels of occupants. This limits the ability of researchers to optimize the overall performance of a group of buildings such as in a campus or community. Finally, it is currently challenging to distinguish between different occupancy profiles (e.g., students, workers), who can have different patterns of using and interacting with their environment. Current energy modeling tools are in fact limited to a building system centered approach, rather than a human centered one. This has limited their ability to capture human actions and behaviors in their evaluation of building performance (Azar and Menassa, 2014, 2012a).

This study fills the identified gap in literature by proposing an Agent-Based Modeling (ABM) framework to comprehensively evaluate the performance of the built environment. The framework is multi-disciplinary and integrates key elements such as people movement and schedules, weather conditions, urban form (e.g., distances between buildings), indoor and outdoor thermal comfort levels, and building energy consumption. Such an integrative approach can offer new insights to help address the complex sustainability challenges of the built environment.

LITERATURE REVIEW

Prior to proceeding with the methodology, this section summarizes literature on the main dimensions of building performance considered in this study: energy consumption, thermal comfort, and occupancy movement in sustainable cities or communities.

Energy consumption

A large number of studies investigate the energy performance of commercial and residential buildings, and evaluate energy conservation measures. The focus of these studies is typically either on (1) building systems and technology, or (2) human behavior and building energy management strategies. For instance, various studies tested improvements related to building envelope or equipment such as the Heating, Ventilation and Air-Conditioning (HVAC) units (Afshari et al., 2014; Chidiac et al., 2011). These studies typically include modeling the buildings of interest using energy simulation software (e.g., EnergyPlus, IES or eQuest), and then testing different technological improvements to current building systems.

In recent years, the influence of human behavior on building energy use has been gaining a lot of interest (Annex 66, IEA, 2014). In fact, several researchers are investigating the impact that occupants and facility managers can have on building energy performance (Langevin et al., 2014; Azar and Menassa, 2012b; Barooah, 2011). For instance, Azar and Menassa (2012b) quantified the impact of individual occupancy actions on the energy performance of typical commercial buildings. Examples of these actions include adjusting thermostat temperature set points and operating equipment and lighting systems.

Thermal comfort

As for thermal comfort, it is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as *the condition of the mind in which satisfaction is expressed with the thermal environment* (ASHRAE, 2004). Based on the above definition, comfort is not a state condition, but rather a state of mind influenced by personal differences in mood, culture and other individual, organizational and social factors.

Acceptable levels of thermal comfort should always be a priority when designing and operating a building, since comfort highly affects the functional capabilities of the occupants (EPA, 2012). This has led to the development of several building codes and regulations such as ANSI/ASHRAE Standard 55-2004 and ISO 7730, setting core compliance principles and guidelines (ASHRAE, 2004). Concurrently, thermal comfort has been the focus of a large number of academic studies (Djongyang et al., 2010; Nicol and Humphreys, 2002; De Dear and Brager, 1998). One such example is the work of Djongyang et al. (2010) who analyzed both rational and adaptive thermal comfort approaches, and presented a first comprehensive overview of the human body thermoregulatory system.

Sustainable cities and occupancy movement

In parallel to the above-mentioned studies, researchers have lately broadened their research focus from individual to groups of buildings (e.g., neighborhood or city level). In general, sustainable city design, construction and operation has gained a lot of attention from engineers during the last years and especially in areas with extreme climates (Alshuwaikhat and Nkwenti, 2002).

In such a macro approach, new elements of building performance become important such as people movement patterns, outdoor conditions and walkability, outdoor thermal comfort levels, to name a few (Rakha et al., 2014; Hopee, 2002). The interactions of these elements are particularly important to study, such as how the movement of people in their urban environment reflects back on their energy consumption or well-being. For instance, Rakha et al. (2014) developed a method to generate building occupancy schedules from activity-based travel surveys. This can improve the modeling of urban mobility and energy consumption demand.

In summary, despite the advancements in each of the fields presented above, literature lacks a clear framework that integrates them for a comprehensive analysis of building performance. Consequently, it is currently challenging to devise strategies that simultaneously optimize the various dimensions of sustainable building performance.

METHODS

A model was developed for the purpose of this study using Agent-Based Modeling (ABM). ABM is a technique that allows the user to model individuals, give them attributes, and let them interact within an environment. The description of the model, which was developed in Anylogic 7, follows the ODD (Overview, Design concepts, Details) protocol for describing agent-based models (Grimm et al., 2010).

Purpose

The main goals of the model are: (1) simulate an urban area with several buildings (e.g., campus), (2) simulate people movement and actions within the environment, (3) calculate key performance metrics such as thermal comfort and energy consumption levels, and (4) test and propose strategies to optimize sustainable building performance.

It is important to highlight that the scope of this paper is to showcase a proof-of-concept (PoC) of the modeling approach needed to integrate and study the important core components of a sustainable built environment. The model is highly customizable and can be applied on any urban environment. Furthermore, it is designed in a modular manner to ease future expansions and improvements. Finally, the model is illustrated in this paper using a conceptual campus environment with three types of buildings (i.e., dorm, office, and classroom), and two categories of people (i.e., students, staff). The campus is located in Abu Dhabi, United Arab Emirates (UAE).

Entities, State Variables and Scales

Three types of entities are mainly used to develop the model: the outdoor environment, buildings, and people. Each type is characterized by a set of attributes and variables that change over the simulation time. Table 1 highlights some of these attributes, which are discussed next.

First, the outdoor environment is the geographic area that determines the operation boundaries of the model. In this paper, it represents a conceptual campus environment. Specific attributes or variables that represent the environment are its size, outside air temperature, humidity and air speed. These are based on the location of the studied environment, which is chosen to be in Abu Dhabi, UAE. Abu Dhabi is considered to have a very hot and dry climate, based on ASHRAE Standard 90.1-2010 international climate zone classification (ASHRAE, 2010).

The second category of entities are buildings, which define the indoor built environment. A building in the model can be of three types: a dorm, office, or classroom building. Attributes of each building include indoor temperature (i.e., thermostat setting), indoor humidity and air speed, and calculated energy consumption levels.

People form the third and last type of entities in the model. People are the building occupants or model agents that can be of two types: students or staff members. Each occupancy type is characterized by a certain schedule (i.e., when to move between buildings and how much time to spend in each). To capture these movements, agents have attributes such as geographic position in the simulation environment, moving speed, metabolic rate, clothing level, and calculated indoor and outdoor thermal comfort levels.

As far as the time scale is concerned, one time-step represents 1 minute and simulations are run for 24 hours of a typical day of September (from 00:00 up to 24:00). Finally, the model boundaries are strictly limited to the size of the campus environment, which is 2 square km. Any movement or comfort perception that agents have outside of it are not taken into consideration.

Table 1
Entities characteristics

OUTDOOR ENVIRONMENT	BUILDINGS	PEOPLE
Size (simulation area), temperature, humidity, air speed	Building type (e.g., office), indoor temperature, indoor humidity, indoor air speed, calculated energy consumption	Agent type (e.g., staff), daily schedule, position, moving speed, metabolic rate, clothing level, calculated indoor/outdoor thermal comfort

Design Concepts

The developed model integrates three basic design concepts: people attributes and movement, energy performance, and thermal comfort.

(1) People Attributes and Movement: A schedule is assigned to each type of agents in order to explicitly define their daily routine routes on campus. An example is presented in Table 2, showing the movement schedule of student and staff agents. However, in order to make the movements more realistic, variability was added through stochastic functions applied on the scheduled movement patterns. This was done by creating a Java function in Anylogic called "wander", which makes agents occasionally go to a random location on campus before heading back to their scheduled destination. This function is activated with a probability of 0.3, meaning that people "wander" before going to their destinations for 30 percent of the time. In practice, this represents cases where students or staff decide go to other places on campus (e.g., take a break, meet a colleague). Variability is also added to people moving speeds, which follow a triangular distribution rather than a constant value. Finally, according to Höppe (2002), metabolic rates change based on whether people are moving or at rest. In order to integrate this in the model, one value is defined for people in movement, or who have been at rest for less than 10 minutes. Another value is assigned to people who have be at rest for 10 minutes or longer.

(2) Thermal Comfort: Thermal comfort is function of the tolerance of individuals to the environmental conditions they are subject to. Therefore, a common practice is to measure thermal comfort based on whether people are satisfied or not (Klein et al., 2010). The specific metric typically used is the Predicted Percentage of Dissatisfied (PPD) people, as defined by ASHRAE (2004). For this purpose, the "CBE Thermal Comfort Tool" was used in the model, which was initially developed at the Centre for the Built Environment of the University of California Berkeley (Hoyt et al., 2013). The inputs to the CBE tool are parameters such as temperature, humidity, air speed, clothing level, and metabolic rates. The output on the

other hand is the PPD level. As explained later, at each time-step, the model calculates thermal comfort for each occupant individually. For instance, for agent i, the model gathers information about the agent (e.g., clothing level, metabolic rate) and about its environment (e.g., temperature, humidity, and air speed), based on where the agent is at the current time-step (e.g., outdoor, at dorms, etc.). The model then sends the gathered information to the CBE tool to calculate, using the PPD, whether the occupant is comfortable or not. At the end of the simulation, total comfort levels are compiled by agent and by environment (i.e., outdoor and different buildings).

(3) Energy Performance: Electricity consumption is estimated in the model using energy calculations generated in eQuest, one of the most popular energy simulation software. This is done by modeling the three types of buildings considered in eQuest (i.e., dorms, offices, classes) and running the models using different combinations of parameters (e.g., different set point levels, different schedules, different outdoor conditions, etc.). Results are then integrated in the agent-based model, which fetches the right energy consumption levels based on the current parameters of the agent-based model. As discussed later, future research can include coupling eQuest and Anylogic to get energy predictions in real-time for any combination of parameters. Currently, only the combinations simulated in eQuest and integrated in the agent-based model can be used.

Table 2
Schedules applied on different agent types

TIME	STUDENTS	SERVICE STAFF
00:00	get located at dorms	get located off campus
08:00	go to offices	go to offices
10:00	go to classes	n/a
12:00	go to offices	n/a
14:00	go to classes	n/a
16:00	go to offices	n/a
20:00	go back to dorms	go off campus

Initialization & Input Data

This section describes the initialization process for the outdoor environment, buildings, and agents or people. Starting with the outdoor environment, we have:

- Air Speed: 0.5 m/sec, assumed constant during the day.
- Relative Humidity: 70% (Dubai Statistics Centre, 2009), assumed constant during the day.
- Air temperature: Changes during the day, based on historical averages obtained from (Meteorologisk Institutt, 2014) for a typical September day in the UAE (very hot climate).

Regarding the initialization of the indoor building environment, we have:

- Air Speed: 0.1 m/s (ASHRAE, 2004), assumed constant during the day.
- Relative Humidity: 50% (Berbari et al., 2007), assumed constant during the day.
- Air temperature: 22ºC according to Afshari et al. (2014).

As for agents, different parameters are assigned based on their type:

- Initial location: Students are all initially located in the dorms whereas service staff off campus.
- Average moving speed: Random values are assigned to each one of the individuals that perform a movement, following a triangular distribution. The minim value of the distribution is 0.01 m/sec, the maximum value is 0.40 m/sec, and the most likely value is 0.10 m/sec. The relatively slow values chosen for moving speed capture potential stops that people can take on the way to their destinations.
- Clothing level: It is the same for all occupants and equal to 0.61 clo, where 1 clo equals 0.155 $m^2 \cdot K/W$ (0.88 $°F \cdot ft^2 \cdot h/Btu$). This level of clothing insulation corresponds to light wearing, such as long-sleeve shirt and trousers (ASHRAE, 2004).
- Metabolic rate: Occupants that are indoors typically stand or relax, which according to Hoyt et al. (2013) corresponds to a metabolic rate of 1.2 met, where 1 met equals 58.2 W/m^2. On the other hand, occupants in movement, or up to 10 minutes after a movement, are assigned a metabolic rate of 2 met.

Process Overview and Scheduling

The execution process of the model is shown in Figure 1 and described below. First, all model components are initialized based on the information provided in the previous section. Then, the first time-step of the model is initiated, where the agent loop is activated. Starting with the first agent, the model updates the agent’s characteristics and position according to the schedule assigned. After the agent has performed its movement for that time-step, thermal comfort is calculated based on the environment characteristics that the agent is located in as well as his/her personal characteristics. Then, the same actions are performed for the next agent. After all characteristics and position for all agents have been updated and thermal comfort has been calculated, the model calculates the energy consumption of all buildings for that time-step. The indoor and outdoor environmental conditions for the next time step are then updated and the same process

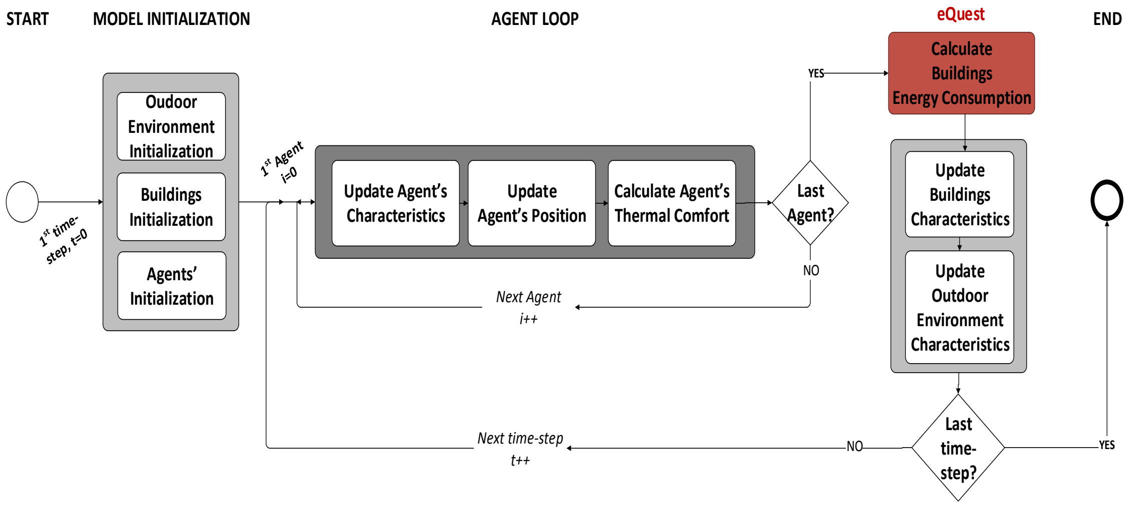

Figure 1 Flowchart diagram describing the performed processes

repeats until the last time step is reached and the simulation ends.

Verification & Validation

Various verification and validation techniques were applied to ensure the technical validity and robustness of the model. These include (1) *Conceptual Validity* through using verified methods and principles such as building simulation models and thermal comfort calculation tools, (2) *Operational/Structural Validity* through techniques such as tracing, graphical representation, and sensitivity analyses, and (3) *Internal Validity*, through changing the variable simulation seeds and comparing the results of the different replications of the model. However, the authors acknowledge that due to the typical variability and uncertainty in human behavior, predictive validation of the model was not performed. This would require data to be collected from hundreds of buildings, which is beyond the scope of this study. To overcome this barrier, the conducted scenario analysis shown next is comparative in nature, where the authors analyzed which changes to the base case model would lead to the best result. In general, the used approach consists of testing which setting or strategy results in the best overall building performance without necessarily predicting absolute energy and thermal comfort levels.

APPLICATION

The proposed model is highly customizable and can be used to evaluate various aspects or dimensions of building performance. This section highlights one application, which is the study of the trade-off between energy consumption and thermal comfort. As mentioned earlier, a conceptual campus environment is modeled with three types of buildings (i.e., dorm, office, and classroom), and two categories of occupants (i.e., students, staff).

The objective of this exercise is to use the model to determine an optimal strategy that maximizes both energy savings and thermal comfort. For this purpose, a Business-As-Usual (BAU) scenario is defined to emulate typical or reference energy consumption and thermal comfort levels. Then, a sensitivity analysis is conducted on key model parameters with high influence on both energy consumption and thermal comfort. Finally, recommendations are made based on the observed results.

The chosen parameters for the sensitivity analysis are the thermostat set point temperature of the three studied buildings. Set points determine the indoor temperature setting of the building, which directly affects thermal comfort levels as well as the HVAC energy consumption loads. As observed in Azar and Menassa (2012b), among different actions that can be taken to alter energy consumption in buildings, changing thermostat temperatures has shown the highest impact, especially in extreme climates that require high cooling or heating loads.

Business-As-Usual

In the BAU case, all three buildings have the same cooling set point temperature of 22°C, which is common in the UAE (Afshari et al., 2014). Assuming that other building characteristics remain constant (e.g., design, HVAC system), daily electricity needs are calculated in eQuest for a typical September day.

As shown in Figure 2, the total daily electricity consumption for all three campus buildings is 5.18 MWh (for a typical September day). The office building accounts for 44 percent of that load, followed by classes and dorms with 29 percent and 27 percent, respectively.

As for thermal comfort, results are summarized in Table 3 and show that 83.3% of occupants feel generally comfortable during the day. This number combines both outdoor and indoor levels, and is mainly driven by the latter since occupants spend most of their days indoors (refer to Table 2).

In this example, indoor dissatisfaction is mostly due to people feeling cold from the set points of 22 ºC, while outdoor dissatisfaction is from the hot and humid conditions typically encountered in the UAE. Note that service staff have higher satisfaction levels as they are typically outdoors only in the morning and the evening, when weather conditions are relatively moderate.

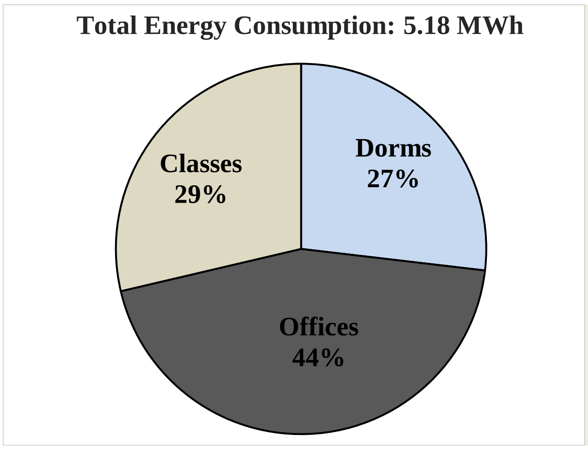

Figure 2 BAU Contribution of each building type to the total energy consumption on a typical September day

Table 3
BAU Scenario (22ºC): Comfort Assessment for both agent types (percentage of time they feel acceptable thermal comfort)

	INDOORS	OUTDOORS	OVERALL
Students	88.2%	19.7%	82.3%
Service Staff	89.0%	41.2%	88.5%
OVERALL	88.3%	23.3%	83.3%

Set point Parametric Variation

After developing the BAU, a parametric variation was conducted on the set point temperatures in order to determine an optimal strategy for energy consumption and thermal comfort. The first step consisted of changing all set point temperatures at once, while the second consisted of individually temperatures of different building and test different combinations.

(1) Simultaneous set point changes: Figure 3 illustrates the observed changes in energy savings and thermal comfort levels when gradually increasing cooling set points from 22 ºC to 26 ºC. In general, the higher the set point, the bigger the potential for energy savings becomes. A maximum energy savings of 10 percent is observed for the most extreme scenario of 26 ºC. However, a different trend is observed for thermal comfort. In fact, comfort levels start decreasing for temperatures higher than 24ºC, mainly due to heat discomfort from high indoor temperatures. As a result, the best scenario identified in this step is a set point setting of 24ºC, as it has shown to improve both energy savings and thermal comfort levels by around 5.8 percent.

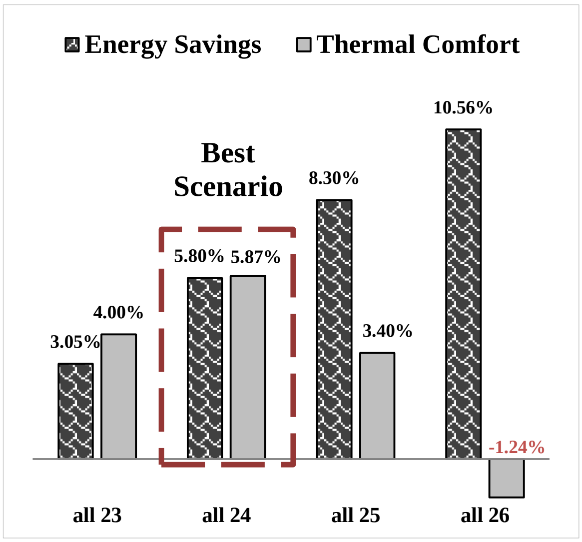

Figure 3 Parametric Variation Step 1 Results - Improvements from BAU

(2) Individual set point changes: This step builds on the results obtained above by starting with the best-identified scenario (i.e., all buildings at 24ºC) and trying to find further improvements. Keeping in mind that a set point of 25ºC in all buildings deteriorates comfort levels, an alternative strategy would be to relax building set points by 1ºC above 24ºC for each building individually. Results are shown in Figure 4, identifying a new optimal scenario with a thermostat cooling set point of 25ºC for the classroom building, and 24ºC for the rest. This resulted in energy savings from the BAU scenario close to 6.8 percent (i.e., a 1 percent increase from the previous phase). On the other hand, thermal comfort levels observed a small decrease from the previous phase (i.e., 0.3 percent). The trade-off between energy conservation and thermal comfort was minimal in this situation, confirming the newly identified best case scenario. The low observed impact on thermal comfort can be related to the fact that the classroom building is not used by staff members, and used only for short periods by students when they attend classes (Refer to Table 2). This made the classroom building a good candidate to relax set point temperatures without compromising overall thermal comfort levels.

A further analysis of thermal comfort levels for the best scenario is presented in Table 4, distinguishing between indoor and outdoor thermal comfort levels for both students and service staff. Results indicate a 2 percent difference between the indoor thermal comfort levels of students and service staff. This difference is consistent with the results and analysis presented earlier, confirming the validity of the results and the optimal strategy that was identified.

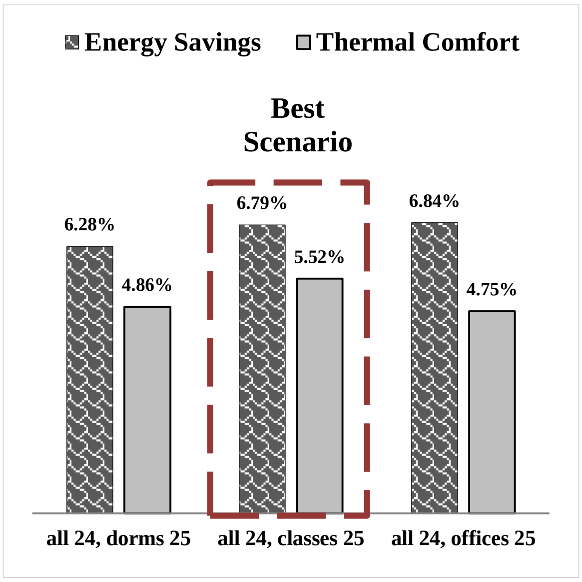

Figure 4 Parametric Variation Step 2 Results - Improvements from BAU

Discussion

The example above illustrates some of the main capabilities of the model such as simulating an urban area with several buildings, modeling different types of occupants, emulating their movement between buildings, calculating their indoor and outdoor thermal comfort levels, and calculating building energy consumption levels.

The model is then applied to offer insights regarding where and when the energy performance of a group of buildings can be improved without compromising thermal comfort. Following a two-step parametric variation process, it was found that relaxing temperature set point in the classroom building can lead to both important energy savings and thermal comfort improvements. The best-case scenario showed the lowest trade-off between energy conservation efforts and thermal comfort levels, resulting in improvements from the BAU case of 6.8 and 5.5 percent, respectively.

Finally, it is important to note that the calculated thermal comfort levels include both indoor and outdoor levels, and account for how long each occupant spends time in different buildings. Capturing such interactions between people and their multiple built environments is an important advantage of the proposed model over traditional building simulation software (e.g., EnergyPlus, IES, and eQuest). These consider one building at time and do not account for people movements and exposure to outdoor weather conditions. As a result, these models cannot capture the overall performance of a stock of buildings such as in a community or a city. This further supports the need for the proposed model, which uses a human-in-the-loop approach to optimizing the overall performance of a stock of buildings.

Table 4
Optimum Scenario (Classes 25°C, Dorms & Offices 24°C): Comfort Assessment for both agent types (percentage of time that they feel acceptable thermal comfort)

	INDOORS	OUTDOORS	OVERALL
Students	93.0%	19.7%	86.7%
Service Staff	94.7%	41.2%	94.2%
OVERALL	93.3%	23.3%	87.9%

LIMITATIONS AND FUTURE WORK

Prior to concluding, it is important to mention some of the limitations of this research, guiding future work on the topic. First, assumptions were made in regards to some of the model parameters. One such parameter is the outdoor relative humidity, which was assumed constant over the course of one day. Another parameter is the cooling set point temperature, which was considered the same for occupied and unoccupied periods (e.g., weekends). While this assumption is not necessarily reflective of reality, the goal of this paper was to illustrate the integration of the various elements of building performance, an objective that was successfully achieved. Future research can involve expanding the model capabilities and collecting data to reduce the number of assumptions made.

Second, as explained earlier, the integration of eQuest runs in the model was done statically. Future research can couple the proposed model with commercial energy simulation software to simulate in real time the impact of human actions and movements on building energy performance. This will also allow linking the number of people present in buildings at each time step with building performance (e.g., energy consumption levels in real time).

Third, as mentioned earlier, validation was limited to technical rather than predictive validity. Future research can focus on testing the model on a large number of buildings and calibrating its parameters for increased accuracy in results.

CONCLUSION

This paper illustrates a conceptual framework to comprehensively simulate human attributes and characteristics, link them to the performance of the built environment, and help find solutions to optimize the design and operation of sustainable buildings. This was made possible by developing an agent-based model that integrates key dimensions of building performance including people movement and interaction with their environment, building energy consumption, and thermal comfort. The contributions of this work are significant as the proposed approach sets the ground for future research on the complex and multi-disciplinary challenges facing our built environment. Moreover, the proposed model can eventually be integrated in commercial building and city modeling software, capturing the missing human dimension to design smarter and more sustainable cities.

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