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Building Operations Emulator: Integrating Interactive Building Performance Simulation into Building Operators Training

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Abstract

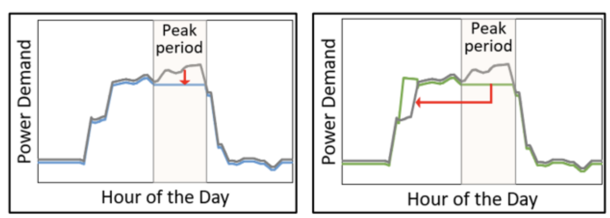
Smart building operations depend on the competencies of building operators. However, current lecture-based training only partially reflects the dynamic nature of actual buildings, inhibiting building operators from learning practical building interaction under diverse situations. This paper proposes a building operations emulator (BOEm) that integrates interactive building performance simulation into building operators' training. BOEm is a versatile simulation-based learning platform providing immersive training experiences to instruct realistic building responses with realistic building automation system (BAS) interfaces. The resulting enhancement of operator skills will pave the way to overcoming barriers hindering smart building operations.

Introduction

Grid-interactive efficient buildings (GEBs) mark a new era in building energy management, integrating smart technologies and distributed energy resources (DER). GEBs can improve demand flexibility by controlling energy use according to grid signals. For example, GEBs allow load shedding (reducing electricity supply to specific areas) or load shifting (moving electricity consumption from peak hour to off-peak hour), shown in Figure 1, for the robustness and sustainability of the electric grid. Due to the increasing load flexibility potential (200 GW by 2030 in the U.S.), this strategy is expected to open a $15B/yr market (Neukomm, Nubbe, and Fares 2019; Hledik 2019). The successful implementation of this strategy, especially without compromising occupant comfort, heavily depends on the competencies of building operators.

According to the Green Building Career Map developed by the Interstate Renewable Energy Council (IREC 2021), the primary qualification for getting a job as a building operator is extensive experience in maintenance or mechanical roles. Most employers prefer applicants who can repair various structures and systems, including heating, ventilation, and air conditioning (HVAC) and mechanical, electrical, and plumbing (MEP) systems. As such, facilities and property managers often seek staff that can reliably operate the building and troubleshoot and fix equipment when needed. Most classroom-based education happens in trade schools and union-based training programs to become licensed in these fields. This trade-specific knowledge could be the last classroom-based education that many operators will have, leaving building operators' training to happen on the job.

In terms of training for building operations specifically, there are post-secondary programs such as the Franklin Cummings Tech Associate Degree in Building Energy Management (Benjamin Franklin Cummings Institute of Technology, n.d.) as well as certificates such as the Building Operator Certification (BOC) (Putnam et al. 2002) provided by the Northwest Energy Efficiency Council (NEEC), which focus on teaching the management of HVAC systems and building automation systems (BAS).



(a) (b)

Figure 1. GEBs can improve demand flexibility via (a) load shedding and (b) load shifting.

However, the 2020 Job Task Analysis Survey (NEEC 2020) highlights an insufficiency in the number and the training of operators. The current entry-level training may use BAS simulators, but these simulators do not fully replicate the dynamic feedback loops within buildings. Furthermore, on-the-job training (OJT) is still required, limiting the variety of situations an operator can experience. Additionally, lecture-based learning may inhibit practical interaction with buildings. This gap underscores the urgent need for a comprehensive training approach that improves operator GEB literacy and includes instruction on occupant-centric control (OCC) to ensure occupant satisfaction (Langevin 2019).

To enhance current building operator training methods, this paper introduces the Building Operations Emulator (BOEm). The proposed BOEm integrates a building performance simulation into BAS software using the industry standard BACnet protocol. It leverages the functionality of NREL's Alfalfa (Benne et al. 2018), a web service that facilitates real-time interaction with EnergyPlus (Crawley et al. 2001) building models. Consequently, it provides immersive training experiences for operators, allowing them to understand realistic building responses, such as setback recovery duration and zonal temperature variation. This emulator can simulate various building types and simulation settings, allowing operators to experience managing diverse building characteristics such as sizes, HVAC system types, and climatic conditions. This adaptability enables comprehensive experience-based training, supplementing the current curriculum for entry-level building operators.

In summary, the primary contribution of this work is the development of the BOEm as a versatile simulation-based learning platform that can reduce the initial need for OJT for entry-level positions.

Background

The following section outlines the contexts relevant to the proposed BOEm's motivation. Firstly, we explain the importance of GEBs and BAS for intelligent building energy management. Secondly, we highlight the opportunities for improvement in the current training of building operators that limit the effectiveness of GEBs and BAS. Lastly, we present the potential of building performance simulations to improve the training of building operators.

Grid-interactive efficient buildings (GEBs)

GEBs are energy-efficient buildings that continuously use smart technologies and on-site DERs to provide demand flexibility while co-optimizing energy cost, grid services, and occupant needs and preferences (Neukomm, Nubbe, and Fares 2019). GEBs allow improved demand-side management through smart technologies, including but not limited to advanced controls, sensors and models, and data analytics. The primary characteristics of GEBs include (Neukomm, Nubbe, and Fares 2019):

- **Efficient:** Minimization of demand on grid resources and infrastructure via persistent low-energy usage
- **Connected:** Two-way communication with flexible technologies, the grid, and occupants
- **Smart:** Analytics supported by sensors and controls co-optimizing efficiency, flexibility, and occupant preferences
- **Flexible:** Flexible loads and distributed generation/storage used to reduce, shift, or modulate energy use

These characteristics are achieved by actively coordinating the whole building system based on grid and occupant conditions by monitoring the operating condition of individual equipment.

- Supporting pre-cooling/heating and coasting for long periods for a building with a significant amount of thermal mass to contribute to load shedding/shifting.
- Incorporating occupancy, occupant preferences, electricity prices, and grid signals into account to actively change cooling/heating set points.
- Considering owner and occupant priorities for thermal comfort and load shedding in priority order.
- Adjusting solar heat gain to reduce cooling/heating needs through dynamic windows with automatic shading.

These capabilities allow GEBs to go beyond the traditional capabilities of energy efficiency and demand flexibility. However, there are still barriers to adopting GEBs (Satchwell et al. 2021). The root causes of these barriers include but are not limited to lack of interoperability, technology too costly and complex, lack of incentive, and lack of understanding from operators. Namely, building operators have an important role in adopting and taking advantage of the potential of GEBs.

Building automation system (BAS)

BAS, also known as building management system (BMS) or building energy management system (BEMS), is a centralized control system of a building that allows the orchestration of HVAC, MEP, shading, access control, security, and other interrelated systems. A typical BAS consists of sensors/controllers attached to terminal units (e.g., rooftop unit, heat pump, fan), low-level controllers (e.g., programmable logic controllers), and high-level controllers (e.g., human interface devices). These components interact through a communication protocol such as BACnet (ANSI/ASHRAE 2016).

The objectives of Building Automation Systems (BAS) are to enhance occupant comfort, increase the efficiency of building operations, reduce energy consumption, improve security, and aid in making better decisions about future investments. For instance, a BAS can maintain the temperature of a building within a specified range, supply light to rooms based on occupancy, monitor system performance and device malfunctions, and alert building maintenance staff in the event of any issues. Due to these benefits, the adoption of BAS is on the rise, especially in commercial buildings.

The Commercial Buildings Energy Consumption Survey (CBECS 2021) reported that more than 40% of commercial floorspace were equipped with BAS for heating/cooling in 2018. As the advancement of Internet of Things (IoT) technologies allows BAS to provide centralized and advanced monitor/control functions for the equipment, the adoption of BAS is no longer considered optional (J2 Innovations 2022). As a result, the global building automation market exceeds $120B (Himeur et al. 2023), and some reports expect it to grow beyond $200B by 2030 (P&S Intelligence 2022).

However, even though BAS allows automation of building operations, building operators still play an important role in supervising the operation of BAS. Building operators should be familiar with BAS to take advantage of its benefits in this context fully.

Building operators training

Since there is usually no strict licensing requirement to operate buildings, entry-level building operators might start their careers right out of high school. Seeking growth and job security, entry-level building operators might pursue trade licenses such as refrigeration or electricity. This type of credential will make them desirable for multiple industries and allow them to perform in-house tasks requiring licensing. Regardless of previous mechanical or electrical skills, entry-level building operators still need to learn the specific nuisances related to occupant comfort and energy efficiency. Candidates learn these nuisances as they become proficient with controls and BAS, and this could take years of experience. This knowledge could be acquired through training specific to building operations (IREC 2021).

Building operations training programs have improved the skills of building operators through different approaches. For example, NEEC has provided lecture-based BOC programs. In contrast, some other programs, like iConnect training program, utilize BAS simulators (an example shown in Figure 2) to provide hands-on experience in a BAS system. Training platforms like iConnect are effective in terms of understanding how building controls work and can be an excellent practice for troubleshooting and fixing BAS components. For example, learning how a thermostat is connected to the system, troubleshoot an actuator, and perhaps how to replace it if necessary. In other words, they provide helpful knowledge for a technician, more so than an operator responsible for making decisions that will impact building energy and its occupants.

Figure 2. An example of the BAS simulator used for the iConnect training program equipped with sensors and controllers for hands-on experiences.

Yet, buildings are complex systems, and many training programs still struggle to teach even a basic level of proficiency in the interdisciplinary foundations of building science fundamentals, BAS, OCC, and GEBs. One of the top barriers is a lack of hands-on experience in whole-building operations, which is necessary for the building operators to apply proper coordinate strategies to different sizes/types of buildings with diverse characteristics.

Therefore, a training program is necessary for operators to improve their literacy of GEB. The program should also include content on maintaining occupants' indoor environmental quality (IEQ) expectations, possibly through OCC, to ensure occupant satisfaction with GEBs initiatives.

The limitations of current lecture-based training and testbeds can be summarized as follows:

- Building physics is not well incorporated into the existing BAS simulator, which makes it difficult for the building operators to predict the response from the actual buildings.
- The existing testbed has fixed or limited settings, which makes it difficult for building operators to generalize their skills to different types of buildings.
- The components related to GEB literacy (e.g., OCC, DER) associated with building science fundamentals are not well incorporated.

Building performance simulations

Building performance simulation, such as EnergyPlus (Crawley et al. 2001), replicates the aspects of building performance (e.g., thermal, lighting, airflow) founded upon the basis of fundamental physical principles and engineering practice. Its objective is to quantify the building performances, such that the simulation results can guide the design and construction of buildings (Wilde 2018).

Traditionally, building performance simulations are mainly adopted to quantify the long-term performance of buildings, such as yearly simulations to test the accordance with the national and state building energy codes, to guide the design of buildings. However, with the advancement of computation power and the fidelity of the simulation models, building performance simulations are increasingly adopted to quantify the short-term or real-time performances of buildings (Ramaraj and Sparn 2022), such that the simulations can guide the real-time control and/or operation of buildings.

Inspired by this opportunity, we claim that building performance simulations can be incorporated into building operators' training, addressing the limitations of the current lecture-based building operators' training. Specifically, efficient building performance simulations can provide realistic building responses in real-time, allowing immersive training experiences founded upon fundamental physical principles and engineering practice.

Method

This section outlines the technical foundation and the architecture of BOEm.

Framework for co-simulation

Co-simulation is a technique that refers to the joint simulation of different standalone subsystems, where the subsystems are coupled to each other. Given high-fidelity simulations of the subsystems, co-simulation allows accurate simulation of a large and complex system, by synchronizing the inputs and outputs of subsystems. Due to its interdisciplinary nature, co-simulation is being actively adopted in various disciplines, especially when the interaction between different disciplines is necessary (Gomes et al. 2018).

We developed a co-simulation framework for the proposed BOEm, combining an accurate building performance simulation module and BAS software. Here, the BAS software contains a user interface such that the user can feed the building control inputs to the building performance simulation module. Then, the simulation module provides realistic building responses following the building control inputs.

Our approach uses Alfalfa (Benne et al. 2018) to implement the building performance simulation module. Alfalfa is a web service developed by NREL that enables runtime interaction with EnergyPlus building energy models. Founded upon EnergyPlus, Alfalfa supports various sizes of timesteps ranging from 1 minute to 1 hour (number of timesteps per hour should be evenly divisible into 60), and the total simulation length can be longer than 1 year. In other words, Alfalfa can support modelling a short-term behavior as well as a long-term behavior of building model. Alfalfa transforms building energy models into virtual buildings by providing industry standard building control interfaces for interacting with models as they run. An external client (i.e., the user) can interact with the virtual buildings over representational state transfer (REST) APIs, such that the user can observe simulation data and provide control input. Alfalfa leverages widely adopted open-source products and is architected according to best practices for a robust, modular, and scalable architecture. This architecture allows Alfalfa to simulate multiple virtual buildings with the same or different configurations simultaneously; thus, the user can quickly test various building management scenarios for the same building or a scenario involving the orchestration of multiple other buildings. A recent update on Alfalfa also exposes simulation data points as BACnet points ("Alfalfa BACnet Bridge" 2023), allowing BAS software to interact with the virtual building as if interacting with actual building systems.

The co-simulation framework is flexible: additional simulation modules can simulate even more realistic building operation scenarios. For example, modules simulating the signals from the electric grid or the behavior of occupants can be developed and coupled with the building performance simulation module such that the user can learn the best building management strategy to prevent unwanted occupant setpoint overrides under unpredictable electric grid status.

Building Operations Emulator (BOEm)

Founded upon the co-simulation framework, we propose an architecture of BOEm, shown in Figure 3. BOEm allows the building operators to use an existing training unit (e.g., a BAS simulator) or virtual training unit (e.g., a graphical user interface) to operate building performance simulation through BAS software using BACnet protocol, such that they can improve their GEBs literacy based on the realistic responses from the building performance simulation. Following the default implementation of BACnet/IP, the IP port for communication is 47808, which is written as 0xBAC0 in hexadecimal. The interaction between the user and BOEm can be summarized as follows:

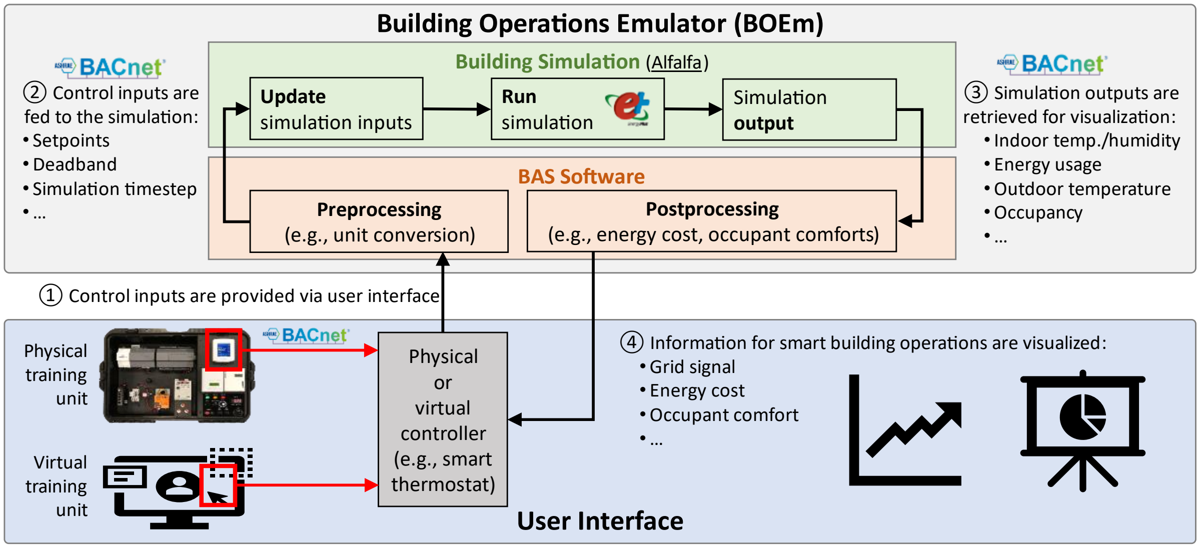


Figure 3. The architecture and operation of the proposed building operations emulator (BOEm)

- **Step 1:** The user provides control inputs (e.g., cooling/heating setpoints, deadband) via the user interface, either physical or virtual training unit.
- **Step 2:** Control inputs are fed to the building performance simulation living inside Alfalfa. Preprocessing of control inputs (e.g., conversion between degrees Fahrenheit and degrees Celsius) is performed if needed.
- **Step 3:** Building performance simulation proceeds with the control inputs (either in real-time or faster/slower time scale), and then outputs (e.g., indoor temperature/humidity, outdoor temperature, energy usage) are retrieved.
- **Step 4:** Retrieved information is visualized to allow the user to decide subsequent actions (i.e., back to Step 1). Postprocessing can be performed to provide additional contexts, such as grid signal, energy cost, and expected occupant comfort level.

The proposed architecture of BOEm provides the following core features addressing the limitations of current training programs:

- Building operators can improve their skills based on the realistic responses from the building performance simulation (e.g., setback recovery duration, zonal temperature variation), as the simulation is founded upon Alfalfa. This web service enables runtime interaction with EnergyPlus building energy models.
- By changing the simulation settings, building operators can generalize their skills to buildings with different characteristics (e.g., sizes, HVAC systems) and environments (e.g., climate).
- BOEm can be customized to provide additional information (e.g., occupant needs, grid signal), which is helpful for improving GEB literacy.

Results

Building model

As a representative example of building models, the prototype standard 90.1 small-commercial building model (Goel et al. 2014) developed by Pacific Northwest National Laboratory (PNNL) is used as the target building model. Figure 4 and Table 1 show the prototype's main characteristics. For more information about the prototype, the readers are referred to the official documentation by PNNL (Goel et al. 2014). BOEm supports any EnergyPlus building models and thus can be applied to different building models. Also, the user interface can be adaptably designed based on the number of zones.

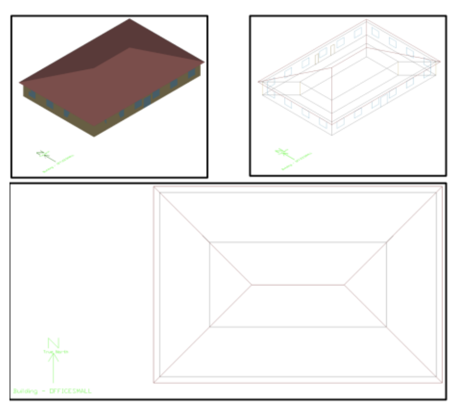


Figure 4. Isometric views (top) and top view (bottom) of the prototype standard 90.1 small-commercial building

Table 1. The main characteristic of the prototype standard 90.1 small-commercial building model

Item	Value
Total floor area	550 ft^2 (90.8 ft x 60.5 ft)
Location	Zone 5B: Denver, CO (cool, dry)
Available fuel	Gas, Electricity
Building type	Office (Small)
Aspect ratio	1.5
# of floors	1
Window fraction	24.4% (South) and 19.8% (Other directions)
Window sizes	6.0 ft x 5.0 ft
Window location	Evenly distributed along façades
Shading geometry	None
Azimuth	Non-directional
Thermal zoning	Perimeter zone depth: 16.4 ft Four perimeter zones, one core zone, and attic zone. Percentage of floor area: perimeter 70% and core 30%
Floor to ceiling height	10 ft
Glazing sill height	3 ft (top of the window is 8 ft high with 5 ft high glass)
Heating	Air-source heat pump with gas furnace as backup
Cooling	Air-source heat pump
Distribution and terminal unit	Single zone, constant air volume air distribution, one unit per occupied thermal zone

Communication between Alfalfa and BAS system

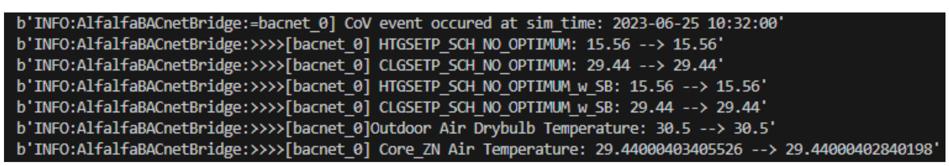
The proposed BOEm is founded upon the coupling between the building performance simulation module (implemented with Alfalfa) and the user interface module (implemented with BAS software). Figure 5 shows the communication between Alfalfa and the BAS software in an actual scene. First, Alfalfa continuously simulates the indoor environment data of virtual building(s) and reports the data as BACnet objects accessible by the BAS software (Figure 5(a)). Then, the BAS software receives the indoor environment data, and feeds the building control inputs back to Alfalfa (Figure 5(b)).

Training scenario

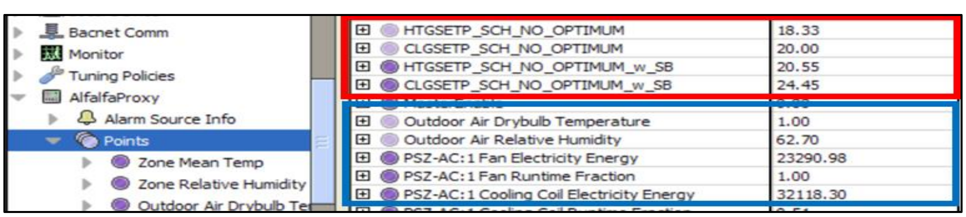
The current implementation of BOEm includes the **pre-cooling scenario**, where the user is required to adjust the pre-cooling time period to understand its impact on the peak demand and total energy cost. It is a crucial scenario for OCC, as it needs to consider the interaction between the following components: (1) the amount of peak energy to be shifted to ensure the robustness and sustainability of the electric grid, (2) the influence on occupant comfort considering occupancy schedule, (3) time-of-day rate of electricity, if applicable, and (4) understanding of the responses of the target building (e.g., thermal mass, setback recovery duration) to ensure that pre-cooling period can reduce the indoor temperature during the peak period. The underlying virtual building provides rich information in real-time, allowing the implementation of additional scenarios for the extension of the BOEm to cover a wide variety of building management scenarios (e.g., controlling the plug loads).

User interface

In this paper, a virtual training unit, which is applicable to both in-person and online training sessions, has been developed. The user interface is founded upon Niagara



(a)



(b)

Figure 5. The communication between Alfalfa and BAS system: (a) the indoor environment data continuously simulated by Alfalfa, and (b) the indoor environment data received by the BAS software (Blue) and the building control inputs fed back to Alfalfa (Red)

N4 ("Niagara Framework" n.d.). Still, it can be customized as per the needs of different use cases, for example using open-sourced Sedona Framework ("Sedona Framework" n.d.). Figure 6 shows the components of the virtual training unit, which help the user to become familiar with the pre-cooling scenario by interacting with a virtual building model. Each component is designed to guide students as follows:

- **Main menu** (Figure 6 (a)): This component provides the overall information of the building and outdoor environment in real-time (e.g., the indoor temperature of each zone, current setpoint, power), and allows the user to navigate different components of the virtual training unit.
- **Setpoint scheduler** (Figure 6 (b)): This component allows the user to control the setpoint using a calendar-like interface, where the user can define different building management strategies (e.g., pre-cooling for different days of the week).
- **Temperature & energy consumption history** (Figure 6 (c)): This component visualizes the history of indoor/outdoor temperatures and energy consumption so the user can review the influence of different pre-cooling strategies on the building system after implementing them.
- **Savings calculator** (Figure 6 (d)): This component allows the user to calculate the overall energy and cost savings after implementing pre-cooling strategies. The calculation of energy and cost savings is implemented under the hood of BOEm. The energy cost during the peak and off-peak periods can be configured assuming different conditions, such that the user can adaptively learn different optimal strategies. For example, suppose energy cost during the peak period is the same as the off-peak period. In that case, implementing a pre-cooling strategy does not provide any cost-saving benefits to occupants.

Demonstration

An undergraduate researcher at Northeastern University completed an internal test according to the basic description of the pre-cooling scenario described above. The user could interact with the virtual building of BOEm, easily become familiar with the user interface, and learn how to control the pre-cooling period for load shifting (Figure 6 (c)).

Specifically, it is shown that 5-10% of the demand during the hottest period of the day (about 1.2 kWh) has been shifted to off-peak periods by implementing the pre-cooling schedule, which can improve the electric grid's robustness.

Physical training unit demonstration

Connecting the BOEm to a physical BAS training unit, as shown in Figure 2 yields a hands-on learning activity that combines real building dynamics, a commercial BAS interface, and actual field equipment. A video demonstration is available on YouTube (Michael Kane 2023).

Discussion

Our results demonstrate the emulator's potential for the users to be familiar with the pre-cooling scenario, founded upon realistic responses from a virtual building. This provides a platform for more authentic training experiences for operators. The initial impact of this work lies in its potential to revolutionize building operators training by introducing a more realistic, dynamic, and customizable platform for GEB-focused instruction.

A key benefit of using an energy simulation is the ability to experiment with load shifting scenarios that rely on the thermal mass of the building. Aside from learning grid interactive practices, this superior training platform allows students to get a feel for the thermodynamics of a real building. In other words, observing how long it takes to raise or drop the temperature of a space, or perhaps the time it takes to get to equilibrium once a change is implemented. Another key benefit is the ability to simultaneously run a simulation for the **same building** with the **same weather file** under “business as usual” conditions. Thanks to this feature students can observe the direct impacts in power and energy of their interactions.

We demonstrated a pre-cooling scenario in this paper, which shifts demand from the late afternoon to the early afternoon (Figure 6C). Additional training scenarios can be implemented, as per the needs of the building operator community. The examples include:

- Scenario 1: Depending on the type of building, the Peak kW Demand might occur during morning start-up. In a fully electrified building in a cold-weather climate, peak demand might occur on the coldest morning of the year as opposed to the hottest afternoon. Using the BOEm, students could implement strategies such as pre-heating or cooling spaces **overnight** and observe the reduction in demand during morning start-up.

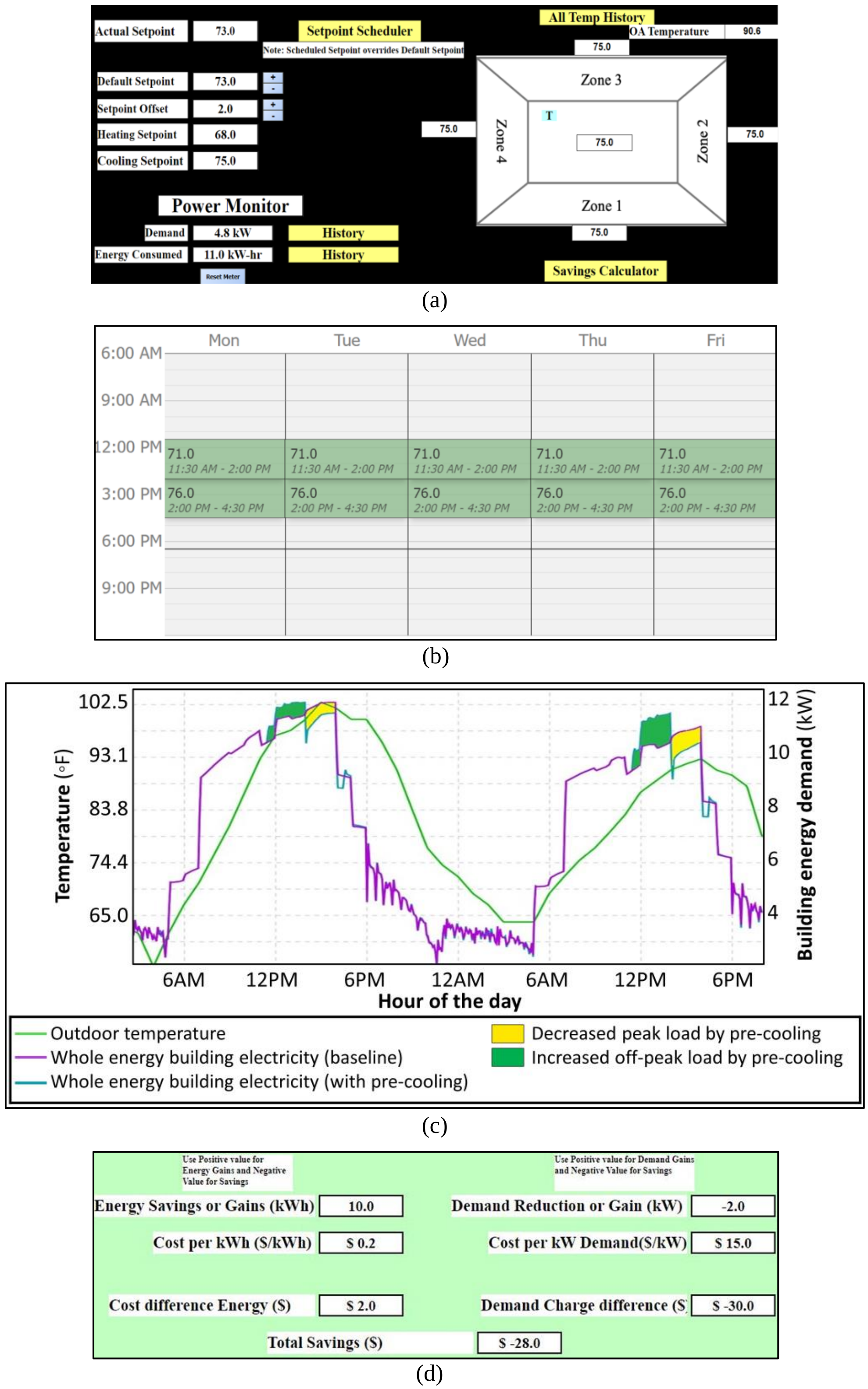


Figure 6. The user interface (virtual training unit) of BOEm: (a) the main menu, (b) setpoint scheduler, (c) temperature & energy consumption history, and (d) energy/cost savings calculator.

- Scenario 2: Instead of reducing the peak demand of the grid (as demonstrated in our pre-cooling example), a building could aim to reduce its own peak demand for cost savings.
- Scenario 3: Instead of focusing on demand, some utility companies implement time-of-use pricing for the energy consumed. For example, the cost of energy might be significantly lower when there is excess solar or wind generation. In this case, the BOEm could be used to practice lowering consumption at specific times of the day, as opposed to common peak times.

In the future, we will demonstrate the use of BOEm in the actual training program named Building Operator: Grid and Occupants (BOGO), which is a part of the BOC program funded by the U.S. Department of Energy under award DE-EE0009742. This follow-up study will guide the future development of the BOEm, based on the feedback from a larger number of students. This is possible as the proposed BOEm has a flexible architecture founded upon widely adopted technologies, where the target building model, the target scenarios, and the user interface can be customized as per the needs of the industry.

Conclusion

The introduction of BOEm marks a significant stride towards enhancing current BAS simulators and testbeds through practical learning experiences. The resulting enhancement of operator skills will enable them to better deliver demand flexibility and OCC more effectively. This improvement can pave the way to overcoming the barriers hindering smart building operations, further leveraging the potential of GEBs.

The BOEm was initially designed for building operator workforce development. However, integrating energy modeling dynamics into a BAS is an innovative feature that could also be beneficial in higher education institutions. For instance, Northeastern University's master's program in Sustainable Building Systems concentrates on the design and operations of green buildings. Having a tool to learn the capabilities of BAS would enable higher level students to understand what is achievable through building automation. With the growing complexity in building systems and the need to maintain a comfortable and healthy environment for people, a better understanding of BAS would encourage new and innovative ideas to emerge from the design team to building operators.

Acknowledgment

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