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BOPTEST as a Platform for Building Controls and Grid-Interactive Buildings Workforce Training

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ABSTRACT

Building automation and controls are becoming increasingly complex with the emergence of Grid Integrated Efficient Buildings (GEBs) as well as new highly efficient sequences of operation and data-driven control schemes. However, there remains a significant gap in hands-on training opportunities for building operators and technicians to gain practical experience with advanced control systems in a low-risk environment. This paper presents BOPTEST (Building Optimization Performance Test) as a suitable platform for workforce training in building controls and GEB technologies. BOPTEST provides a suite of standardized building simulation test cases with a REST API, real-time control interfaces through BACnet, semantic models connecting users to building data, and built-in calculation of control metrics and performance indicators. The platform enables trainees to interact with virtual buildings using industry-standard protocols while learning how to implement and innovate control strategies.

The training platform is designed to offer a structured and interactive learning experience for building engineers, helping them effectively develop, learn, and retain skills in fault identification, troubleshooting, and correction. The workflow is divided into three main phases: 1) Setup, 2) Exercise, and 3) Review, each comprising specific activities performed by either the instructor or the student. Initial pilot training sessions have yielded positive feedback from instructors and participants and demonstrates that BOPTEST effectively fills an industry need for a low-risk training resource via simulation of real building control systems, allowing trainees to gain practical experience before working in the field. The platform's ability to provide immediate performance feedback while maintaining familiar industry interfaces makes it particularly suitable for workforce development programs. This work provides a replicable model for leveraging building simulation in control education and training.

INTRODUCTION

In recent years, the notion of grid-interactive efficient buildings (GEBs) with flexible loads have gained importance as a potential resource that can improve the reliability of the electric system at reduced system costs compared to other options. The premise of GEBs is that buildings will be able to receive signals from the utility (or another grid-side entity) representing grid conditions and automatically modify their load profile to support what would be beneficial to the grid's needs (Satchwell et al. 2021). The implementation of this paradigm would require a significant level of automation and control technologies, posing a challenge to the current workforce responsible to operate and maintain buildings. This new

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challenge adds to the existing difficulties of managing buildings effectively. Decades of academic and field studies (Crowe et al. 2020) have shown that building controls have profound impact on commercial buildings' energy performance. However, the vast majority of buildings still experience several control issues (Crowe et al. 2023) resulting in occupants discomfort and waste of energy. Building retrocommissioning aims at fixing these issues and improving building performance. Control troubleshooting and tuning is an important component of this process. Nevertheless, today's building operation and maintenance (O&M) workforce commonly lacks the ability to use building automation systems (BAS) to troubleshoot and fix control-related operational problems. The main contributors to this skill gap are: 1) a large percent of the existing workforce has been retiring in the last 10 years; 2) proficient use of BAS requires both systematic training and significant hands-on practice, which is difficult to acquire "on the job"; 3) there are variety of BAS vendors' products, making it difficult for technicians to be competent in multiple systems; 4) control training is typically taught in 4-year colleges and universities as opposed to vocational schools, significantly limiting the new workforce pool for control technician jobs; 5) BAS training programs with significant hands-on practice opportunities are rare. As a result, it is common to see building operators heavily rely on BAS vendors to come out and perform troubleshooting for their buildings which is often not affordable for many buildings. The gap in BAS training programs for the existing O&M workforce is a key barrier to the wider adoption of GEB enabling technologies. The gaps in classroom training for building operation can be clearly described using the framework presented in Bloom's revised taxonomy (Krathwohl 2002). The taxonomy categorizes cognitive learning into six levels: Remember, Understand, Apply, Analyze, Evaluate, and Create. Traditional classroom training primarily focuses on the lower levels of the taxonomy, particularly remembering and understanding, through basic demonstrations and lectures. Higher levels of the taxonomy are generally acquired through years of experience, trial, and error in the field. Classroom training may provide students with an understanding of the fundamental principles of a BAS and some experience with one version of a BAS or another. However, due to the lack of available low-risk interactive building environments, there are limited opportunities to apply this knowledge by intervening in building operations, analyzing the effects of these interventions, evaluating the effectiveness of the approaches taken, and creating new methods for addressing faults in building controls. Developing a method for teaching these skills in the classroom would better equip the facility management workforce to operate high-performance and efficient buildings.

In 2023, Lawrence Berkeley National Laboratory (LBNL) and the Building Efficiency for a Sustainable Tomorrow (BEST) Center launched a Building Controls & GEB Workforce Training pilot as part of a publicly funded research project. The objective of this pilot was to provide foundational building controls training for the building operators workforce so they can be prepared for owning, operating and maintaining grid-interactive efficient buildings technologies. LBNL and the BEST Center developed and offered customized, modularized training for three distinct cohorts: building engineers and operators, facility managers, and building science instructors at community colleges with HVAC programs. Two of these cohorts offered ~10 hours of in-person hands-on troubleshooting instructions and practices to the pilot participants hosted at LBNL. The curriculum design and delivery leveraged LBNL's unique testbed, FLEXLAB¹ representing physical HVAC systems similar to a smaller sized commercial-scale building system and the new BAS layer to design and deliver this training. The participants were taught to use BAS to perform data analysis and fault detection, interpret and manage alarms, and identify and apply efficiency measures. The training was well attended and received strong feedback from the participants (majority of them were chief or senior engineers) desiring more similar hands-on troubleshooting training. Despite the significant success, the pilot also revealed a limitation in capacity, as only 20 participants could simultaneously interact with the HVAC BAS system for training purposes at any given time. Additionally, this opportunity leveraged a unique testbed (i.e., FLEXLAB), which won't be available at other locations.

To address the need for scaling up such a program, LBNL and the BEST Center have been working on increasing classroom capacity with alternative solutions. One promising option involves leveraging a virtual and interactive building, which allows more participants to simultaneously interact with HVAC systems via BAS. This new tool also offers greater customizability, enabling the simulation of various systems and different building operation scenarios, thereby expanding the range of content that can be taught. This virtual environment must provide realistic scenarios, particularly in the coupling between control systems and the dynamic response of HVAC systems. Tools such as Modelica Buildings (Wetter et al. 2014) and Spawn of EnergyPlus (Wetter et al. 2024) provide these capabilities, enabling the creation of detailed and realistic building scenarios. By incorporating Modelica models through the standardized Functional Mockup Interface (FMI), BOPTEST was developed as a benchmarking tool that integrates high-fidelity HVAC models into a web-based service with a REST API (Blum et al. 2021). This allows users to run standardized simulation scenarios, interact with control I/O points in a standardized way, and obtain a standardized set of KPIs for control performance benchmarking. Furthermore, BOPTEST features a BACnet interface that enables integration with existing Building Automation Systems (BAS), making it possible to simulate HVAC operations in a manner that closely mimics real-world conditions. This combination of realistic modeling,

¹ <https://flexlab.lbl.gov/>

web-based accessibility, and BAS integration positions BOPTEST as an optimal solution to be used as the basis for HVAC training (Fierro et al. 2022). The integration of a commercial BAS interface with the BOPTEST framework allows for the opportunity to educate technicians on activities such as troubleshooting, controls implementation, and diagnosing root causes of HVAC system faults in response to occupant complaints, like “hot and cold” calls. To simulate the control issues that need to be addressed, we build on previous work by (Huang et al. 2018) and (Casillas et al. 2024), which use Modelica to inject faults into a simulated multi-zone Air Handling Unit (AHU) system. BOPTEST enables these simulations to run in real-time, which combined with a realistic interface for operating the virtual buildings, creates an opportunity to improve the effectiveness of classroom training practices.

This paper introduces a novel virtual building platform intended for use in BAS training programs. The training platform is implemented using BOPTEST, and its application is illustrated through a case study that involves identifying a stuck damper in a variable air volume (VAV) box.

DESIGN OF THE PLATFORM

Platform Purpose and Design Requirements

The training platform has been developed to interactively teach building control troubleshooting skills using industry-standard tools. It is designed to be shared with instructors teaching courses on these topics. These instructors can set up scenarios for training exercises, as described in the following section. The scenario presented in the case study section focuses on control issues that affect occupant comfort, as these are situations students are likely to encounter in the field. The platform is particularly focused on enabling students to engage in the higher levels of learning as organized in Bloom’s Taxonomy: 1) applying, 2) analyzing, 3) evaluating, and 4) creating—tasks that have traditionally been challenging to achieve in a classroom setting. To *apply* the information students learn, they must be presented with realistic and relevant training scenarios. These scenarios must be interactive, allowing students the opportunity to take actions based on what they have learned. To *analyze*, the effects of student actions must be easily observable and realistic. The impacts of altering how a building is controlled can be extensive, and changes to one parameter may influence another measured variable that initially appears unrelated. The identification, troubleshooting, and diagnosis of faults in buildings often depend on the analysis of numerous variables and may require multiple interventions and analyses. Providing real-time data on the many variables involved in the fault diagnostics process is critical for learning this skill. To *evaluate*, there must be clear criteria against which to judge one’s actions, as well as data on the effects of those actions. Ideally, this evaluation should be provided promptly so that students can use the feedback to adjust their actions and analysis, thereby accelerating the learning process. Finally, students should have the ability to *create*. They should be able to create their own approaches, actions, controllers, all in a realistic and industry-relevant environment. The training platform has been designed to support each of these learning activities.

Platform Architecture

The platform architecture consists of four primary components: 1) the BAS, 2) the BACnet/IP Network, 3) the BOPTEST ecosystem, and 4) the Scenario Manager, as shown in Figure 1. The platform utilizes a specific *BAS* vendor as the user interface, but the same architecture can be extended to other vendors since the integration is based on the BACnet communication protocol standard, which is used by most BAS and data analytics software. The *BOPTEST* ecosystem includes a “test case” (i.e. building) to simulate and its *BACnet/IP* Interface that runs the simulation and requests key performance indicators (KPIs). The BACnet interface builds a BACnet wrapper around the existing BOPTEST RESTful API interface creating a virtual BACnet device and runs the simulation in real time enabling the interaction with the simulation environment by any of or a combination of these tools. Similar to learning how to use a BAS, learning how to interact with BACnet is crucial due to its ubiquity in commercial buildings. The BACnet interface translates between the simulation model and the BAS. The simulation model is contained within a BOPTEST test case. A test case includes a building dynamic model including HVAC, envelope, embedded baseline controls, and the boundary conditions including weather, occupancy and internal gains. Furthermore, BOPTEST provides standard KPIs to understand how the building is operating, and detailed documentation to understand the test case under analysis. The *Scenario Manager* module has multiple functions. First, it handles the setup of the BOPTEST Test Case scenario, which includes the specific test case to run and the starting time. Second, it can be used to request BOPTEST KPIs and reset the control inputs to the baseline controls. Lastly, it can be used to generate faults in the HVAC, such as emulating a faulty hardware (i.e. stuck damper or valve) or software (i.e. wrong set point, untuned PID controller).

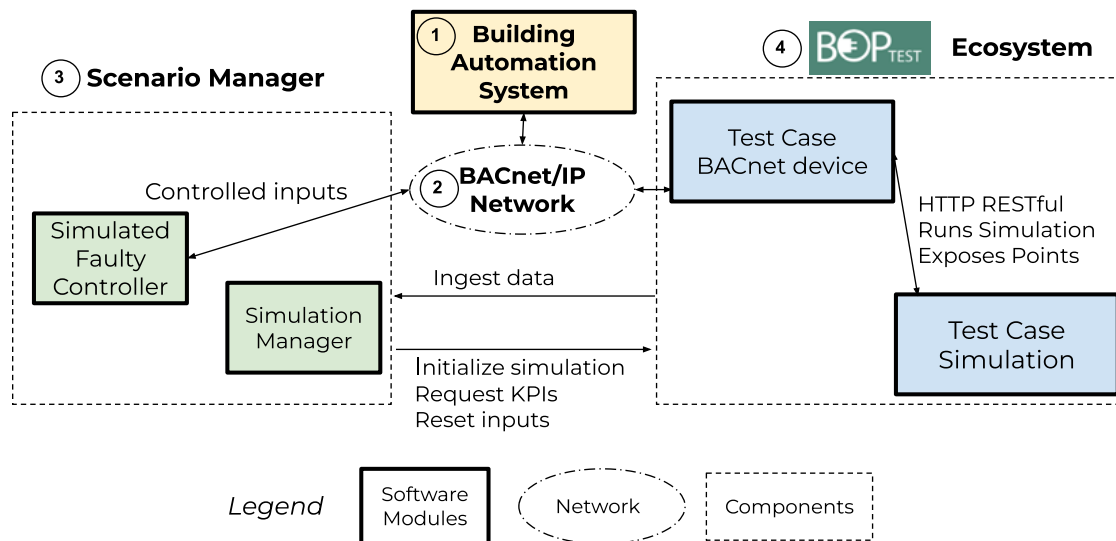


Figure 1: BOPTEST-based training platform architecture includes four core components: 1) a BAS-like interface (vendor-agnostic), 2) a BACnet/IP network enabling real-time communication between simulation and BAS tools, 3) the BOPTEST ecosystem to deploy a test case, create its BACnet interface, run the simulation and request KPIs, and 4) a Scenario Manager for configuring simulations, resetting controls, and injecting faults.

Training workflow

The training platform is designed to provide a structured and interactive learning experience for building engineers, enabling them to effectively develop, learn, and remember skills in fault identification, troubleshooting, and correction. The workflow is divided into three main phases: Setup, Exercise, and Review, each involving specific activities carried out by either the instructor or the student and represented in Figure 2.

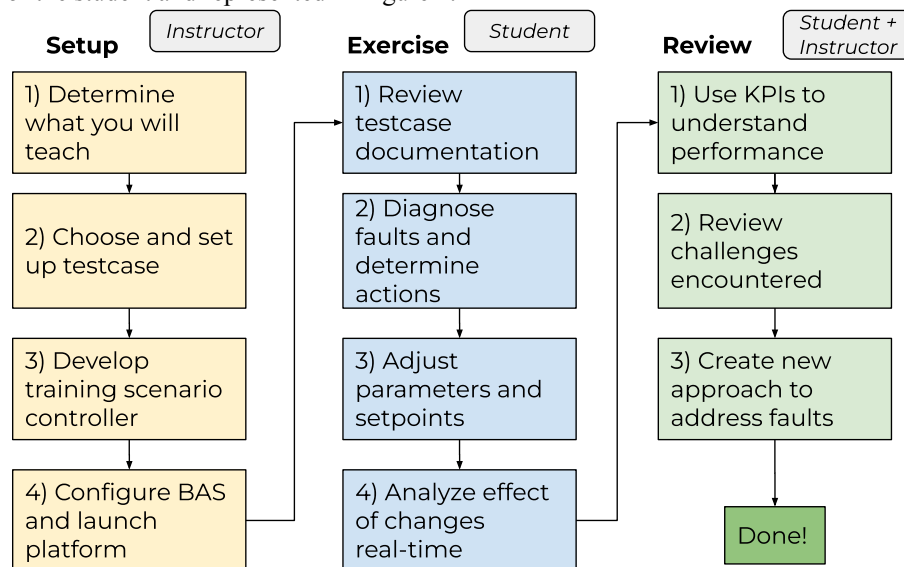


Figure 2: Proposed training workflow

In the *Setup* phase, the instructor begins by determining the specific learning objectives and topics to be covered in the training session. These objectives may be specific skills, such as mechanical fault identification or PID loop tuning, aligned with the skills and knowledge that the students need to acquire. The instructor then selects an appropriate BOPTEST test case that simulates a building scenario where the fault may be present. There are several BOPTEST test cases, each incorporating different building types and mechanical systems. Some faults may only be applicable to specific test cases. Test cases can also be adjusted by changing the Modelica simulation files, which creates the opportunity for specific scenarios to

be set up. BOPTEST should also be configured with a certain simulation time period scenario, such as peak heating, peak cooling, or hybrid conditions. Following this, the instructor develops a training scenario by creating a controller that introduces particular faults or control challenges into the test case, such as a stuck damper. We intend to develop a starting set of faults for training practices, but expect this list to grow over time. Finally, the instructor configures the BAS so that it can connect to the BACnet/IP network and BOPTEST BACnet device. There may be additional BAS configuration required to show the proper graphics or plots that students may start with for an exercise. Additionally, the BOPTEST simulation interface currently runs in real-time when using the BOPTest BACnet functionality. This means that the simulation may have to be started in advance of the exercise if historical data needs to be incorporated into the exercise. Future work will involve investigating the possibility of enabling faster-than-real-time simulation when using the BACnet interface integrated with a BAS. This is a current limitation of the approach, which is further discussed in the discussion section.

During the *Exercise* phase, students begin by reviewing the documentation provided for the selected test case, which includes details about the building model, HVAC systems, control points, and the weather scenario. This understanding is crucial for effective troubleshooting and diagnosis, and it is often the first step in any real fault identification or controls retrofit scenario. The instructor may also include example occupant complaints that could have prompted the fault identification exercise, as this information may be important for fault diagnosis. Students then diagnose the faults introduced in the training scenario by monitoring real-time and historical data through the BAS interface. Students should identify possible actions and parameters that can be adjusted via the BAS, such as temperature setpoints or tuning PID parameters, to support the diagnosis of the fault. They may then adjust various control parameters and setpoints through the BAS and monitor how the data changes in real-time. This interactivity provides essential experiential learning, helping students effectively learn and retain the information and skills within the training scenario. If the simulated faults are mechanical in nature, then identification of the fault and the proper course of action to resolve it would complete the exercise. Alongside the BAS, it would be possible to offer multiple different mechanical adjustments as options for fault correction. However, these mechanical actions would have to be narrowly described and provided as discrete choices to be simulated. This does not enable the creativity that supports effective learning, and has not been implemented at this time. After making adjustments, students analyze the effects of their changes in real-time, observing how variables such as temperature, airflow, and energy consumption are affected. This step provides immediate feedback on the effectiveness of their actions.

In the *Review* phase, both students and instructors use the Key Performance Indicators (KPIs) provided by the BOPTEST platform to assess the building's performance, analyzing metrics such as energy efficiency, occupant comfort, and system stability. Additional KPIs may be added to the exercise pertaining to the health of the HVAC system. For example, one training exercise may be focused on improving PID tuning to reduce valve hunting, which means that a valve opens and closes many more times than it should while trying to achieve a desired setpoint. Decreases in performance due to valve hunting may be visible from the existing high-level KPIs, but a KPI specific to the fault scenario (i.e. reduction of actuator travel) would be an important part of the story. After reviewing KPIs, the instructor leads a review discussion where students discuss the challenges they encountered during the exercise, including difficulties in diagnosing faults or making adjustments, especially misleading steps in fault identification, unintuitive interpretation of data, or especially effective actions in their processes. Sharing experiences and insights helps students learn from each other and reinforces key concepts. Based on the review and feedback, students are encouraged to develop new approaches to address the faults and refine their strategies. They may also be given the opportunity to attempt the exercise again to quickly address a fault and reinforce information, or to build on the exercise with another scenario in a different test case or with different settings.

By following this structured workflow, the training platform ensures that students gain practical experience with building control systems in a realistic and low-risk environment. The combination of hands-on exercises, real-time feedback, and collaborative review sessions trains skills for troubleshooting and optimizing building performance in a memorable and vocation-relevant way.

CASE STUDY

The training framework focuses on a set of faults commonly encountered by building operators during troubleshooting tasks. HVAC symptoms range from zone discomfort and noise to excessive system operation, which can be caused by underlying issues such as mechanical failures, actuator misalignments, and control programming faults (Kim et al. 2021). For instance, zone discomfort due to excessive heat can result from mechanical failures like a damper stuck too far closed or a reheat valve that is leaking or stuck open. Noise complaints can be related to excessive fan flow, potentially caused by high static pressure at the AHU due to an elevated static pressure setpoint or an uncalibrated sensor.

In this study, we focus on troubleshooting a "space too cold" symptom caused by a stuck VAV damper. This fault is typically due to a stuck actuator, which results in higher than desired airflow into the zone. This leads to overcooling and may eventually trigger the VAV reheat valve. At the AHU level, a stuck VAV damper can cause the supply fan to run at higher

speeds than normal due to a drop in static pressure. The increased fan speed results in higher fan energy consumption, while the overcooling may lead to increased heating energy due to unnecessary VAV reheat operation. The BOPTEST framework includes a multi-zone VAV office HVAC system as a test case, making it well-suited to simulate both the fault of interest and the resulting symptoms in the mechanical and control systems. The fault is common and easy to implement in the new framework. The fault injection method, as described by Casillas et al (2024), is achieved by overriding the position of the damper to a constant value. Given that the BOPTEST framework only has access to control points, we simulate the stuck damper fault by setting the control signal value to the stuck position in a secondary "faulted" controller. The feedback from the resulting position is then fed into the baseline controller to represent the saturated PID control loop that would occur in a typical stuck damper fault scenario. To replicate the stuck damper scenario, the process begins by initializing the BOPTEST "multizone_office_simple_air" test case using the Scenario Manager. This step calls the BOPTEST BACnet device interface that deploys a real time simulation of that test case and its associated BACnet device on the specified network to allow the visualization and interaction with all the test case's points on BACnet. Then, the fault injection layer of the Scenario Manager is utilized to introduce the desired fault: overriding the core zone damper position to remain fully open, effectively simulating a stuck damper condition.

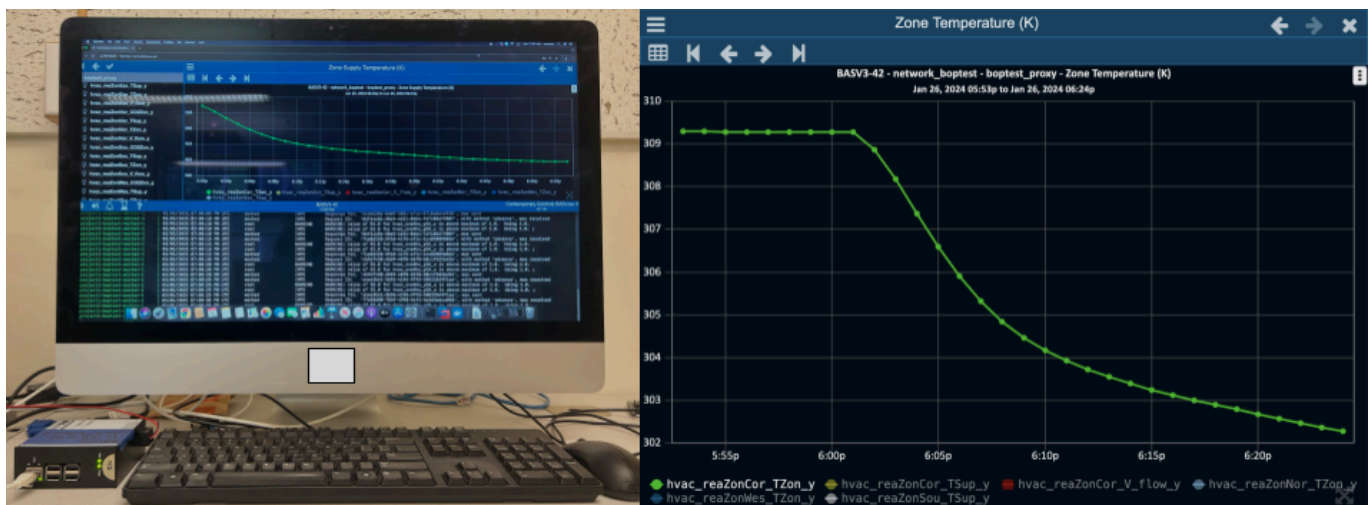


Figure 3: Image of case study. Left, BAS connected to a desktop running BOPTest and BACnet network. The top window shows the BAS interface, bottom window shows the BOPTest simulating the damper stuck fully open fault. Right, BAS trend showing the zone temperature rapidly cooling due to the stuck damper, with the stuck damper fault beginning at 6:00 pm.

DISCUSSION

The fault injection layer can also incorporate additional data points for realistic fault identification. Data from the BOPTEST simulation reflects the control and measurement points from the simulation that are chosen to be exposed by the test case developer, whereas data from a real BAS might be different from what is exposed in a given BOPTEST test case, or from another BAS. This discrepancy is crucial for realistic training in fault identification and correction. For instance, in the stuck damper scenario, BOPTEST sets the damper position to a static value, such as 10%, and reports it to the BAS. However, in a real BAS, the reported damper position value would likely be based on the target value generated by the control system rather than the actual position of the damper. Because the damper is stuck, the PID loop producing this value would gradually increase to 100%. For a realistic fault identification scenario, we should generate the PID value and expose this to the user rather than the simulated damper position written to the model. This may require emulating additional components of the control system within the fault injection layer or exposing additional points from the test case simulation layer, beyond what is already provided by the BOPTEST test cases. However, the simulation test cases still have limitations. As described in Casillas et al (Casillas et al. 2024), there are several nuances in representing HVAC systems in modeling environments that may result in behaviors not found in real buildings. This may lead to less than ideal troubleshooting scenarios. One of the primary challenges is that simulation may not accurately replicate the dynamic responses of real buildings and BAS. For instance, if a damper were fully closed, and airflow through a duct went to zero, the temperature values reported downstream would simply maintain the last known value, because for the simulation, there is no airflow to measure, and no data to update the measurement. This is not how the data would appear in a real building, where the measured temperature would likely follow ambient conditions. This discrepancy can confuse trainees and may lead to

incorrect conclusions about the nature of faults and the appropriate corrective actions. This requires careful handling of specific fault scenarios and understanding of the underlying simulation models, so that these nonphysical values can be replaced with more sensible values or modeling approaches at the simulation or fault injection layers. This increases the learning curve for developing training exercises for this platform.

Another challenge is generalizability to different BAS. Each BAS vendor has unique interfaces and features, and may use different BACnet constructs, which means that the training platform may not fully support the functionality of each BAS. In the case study performed, certain features of the BAS did not work correctly, such as automatically setting the minimum and maximum constraints for writing to different BACnet points. This is because highLimit and lowLimit parameters were not created in the BACnet objects of each point. For integration with particular BAS systems the platform code may have to be edited, which is not ideal. The BOPTEST testcases are also not completely uniform, so the methods for addressing gaps between the simulation models and real buildings may also differ for each testcase.

While the BOPTEST platform currently runs in real-time when using the BACnet interface, enabling faster-than-real-time simulation is currently under active development. This capability would allow for more efficient training sessions by compressing the time required to observe the effects of control adjustments, but it also introduces complexities in synchronizing simulation time with BAS timekeeping, which may run on different systems. Enabling faster-than-real-time simulation that is compatible with industry tools will be an essential feature for extending this platform from training of fault correction to including training of controls design and programming.

FUTURE WORK

There are initiatives within ASHRAE and the building industry to digitize the control delivery process for new and existing buildings (Pritoni et al, 2024). This transition occurs as the building industry moves towards the use of newer, more complex equipment such as heat pumps, thermal energy storage solutions, and high-performance sequences like ASHRAE Guideline 36, as well as those that enable demand flexibility. With these changes, the complexity of the control sequences are also increasing, and today's control design and development workflows might be deemed insufficient. ASHRAE standard 231p Control Description Language (CDL) (Wetter et al. 2019) aims to address this gap by proposing an open, standard and interoperable programming language for building and environmental control logic. CDL supports the simulation and testing of the sequences under a variety of environmental and system conditions and hence the sequence of operations that are being developed can be tested, modified and verified before being deployed onto a BAS controller in a real building. CDL also enables control vendors to formally verify that the sequences that they have programmed meet the specifications set out by the building operator/owner. In a future update of the workforce training tool proposed in this paper, we envision that it can leverage CDL as a platform- and vendor-agnostic programming language to teach control logic programming and verification skills to designers and staff in the field. While CDL natively supports simulation and testing of the sequences, it is usually an open-loop approach. Incorporating CDL into the training framework with BOPTEST enables a closed-loop system, where the trainees can see in real-time how the sequences that they programmed impacts the building equipment and the overall energy and comfort performance.

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