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ABSTRACT

Many commercial buildings have a vast network of sensors as part of their building automation systems (BAS) that allows opportunities for energy consumption and cost savings by deploying advanced control sequences. However, this resource is often underutilized since BAS are typically programmed with simple control sequences with limited potential to deliver on these opportunities. The recent availability of ASHRAE Guideline 36 (G36) with advanced HVAC control sequences supports control retrofits in existing buildings to unlock much of the savings potential. However, barriers such as the lack of standard naming convention of building assets and data points, proprietary equipment and BAS, and the inherent uniqueness of buildings and their systems prevent building stakeholders from adopting any "plug-and-play" implementation of G36. Instead, control vendors must often undertake the manual and labor-intensive point mapping process to identify a data stream's functional and spatial relationship within the HVAC system along with other relevant contexts and map it to the new control sequences. The vendor must carry out the point mapping process in each individual building since the mapping is unlikely to port over to another building. Even for the same building, the point mapping process can occur multiple times if various control vendors implement different control retrofits and/or multiple control retrofits happen over the lifecycle of the building. Then, there is the likelihood that G36 control sequences are programmed uniquely to the building, preventing the same implementation from being reused in another. Therefore, this paper presents a field demonstration of how we leveraged the Brick ontology with BACnet, OpenBuildingControl's Control Description Language (CDL), and open-source support tools to implement scalable and portable advanced building controls. These tools provide standardized semantic descriptions and relationships of the building's assets and data points (Brick), standardized communication protocol to read from and write to the building's BAS (BACnet), and standardized code implementations (CDL) of standardized advanced control strategies (G36). We implemented G36's hot water supply temperature setpoint reset in a Berkeley, CA building for this field demonstration. This field demonstration aims to show how integrating these tools may streamline the deployment of advanced control sequences such as G36 in a consistent manner regardless of differences found across buildings.

INTRODUCTION

Heating, ventilation, and air-conditioning (HVAC) systems are designed to provide buildings with healthy, productive, and thermally comfortable spaces for their occupants. Services provided through HVAC systems account for the largest proportion (44%) of total site energy consumed in US commercial buildings (EIA 2012). Many commercial buildings, especially those with a large floor area, rely on a network of sensors and actuators as part of

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their building automation systems (BAS) to manage the HVAC and lighting equipment (EIA 2022). However, recent pressures to reduce energy consumption and greenhouse gas emissions have pushed building designers and stakeholders to develop new or optimize existing control sequences to decrease the energy use intensity of buildings, including the HVAC systems, without causing adverse effects on their services. Simple control sequence improvements such as wider temperature deadbands, nighttime setbacks, and optimized start/stop times for equipment in existing buildings often have payback periods measured in months (Fernandez et al. 2017) but underutilize the potential of the BAS (Granderson and Lin 2016). Advanced control sequences and fault detection and diagnostic applications take advantage of more features and capabilities of the BAS and associated building energy information systems to reduce total building energy consumption between 5% and 30% (Fernandez et al. 2015; Lin et al. 2020). Although significant energy savings are achieved through advanced control sequences, the complexity of implementing them is higher than the previously mentioned simple modifications. Control vendors for advanced control sequences often undertake point mapping processes in existing buildings to identify pertinent BAS points that will allow them to read and write information required by their control sequences. The labor-intensive point mapping process can cost several hundred dollars per point (Granderson and Lin 2016) and is often limited to the vendor's specific control sequences implementation or BAS platform. As a result, the same vendor or others may need to carry out additional point mapping processes on the same building when new controls or applications are implemented. The higher complexity of advanced controls and applications may contribute to their low penetration rate (Brambley et al. 2005). The current state of building controls is far from ideally being the "plug-and-play" solution that will increase the adoption rate of advanced control sequences. It needs to be streamlined, consistent, and any repetitive effort for onboarding new control sequences needs to be eliminated. Therefore, this paper presents a field demonstration in a Berkeley, California building of how we leveraged standardization projects such as BACnet, the Brick ontology, ASHRAE Guideline 36 (G36), OpenBuildingControl's Control Description Language (CDL), and open-source support tools to implement advanced control sequences that achieve the goal of being consistent, scalable, and portable.

BACKGROUND

BACnet, or building automation and control networks, is a communication protocol that defines a set of rules that allows the BAS network to exchange information in a standardized format, and ASHRAE standing standard project committee 135 is responsible for its continuance maintenance (ASHRAE 2020). BACnet is a significant breakthrough in the BAS industry because building stakeholders are no longer tied to a single manufacturer or control vendor with proprietary protocols to procure equipment and their controls to provide the building services that occupants need. By design, BACnet is an abstraction of the inputs, outputs, and properties of BAS objects but advanced control applications often need more information such as the type and location of a sensor, size of the HVAC zone, or the interconnections of the equipment (Bergmann et al. 2020). This type of information may indeed be found in the BACnet property fields of the BAS object but the text descriptions, including naming conventions, are not standardized, descriptions are often limited, and the information is not queryable (Butler and Veelenturf 2010). We consider the Brick ontology (Brick) to solve these shortfalls (Balaji et al. 2016).

In the same way that BACnet standardized the communication protocol for data transmitted over BAS, semantic metadata schemas standardize the meaning of said data so that it can be accessed and analyzed in a consistent manner. A recent review identified 40 public semantic metadata schemas for various lifecycles stages of the building (Pritoni et al. 2021). The majority are designed for building services such as HVAC, lighting, domestic hot water, and life and fire safety which includes Brick and Project Haystack (Haystack) (Project Haystack 2023). Brick and Haystack were specifically designed for buildings with an emphasis on HVAC analytics and control. We consider Brick because Haystack is based on a tagging system which offers significant flexibility to describe building systems (Quinn and

McArthur 2021) but at the expense of consistency and interpretability that applications developers rely on to build scalable and portable applications. (Fierro et al. 2019).

Brick is an ontology that uses a class hierarchy with three root nodes (*Equipment*, *Point*, and *Location* and shown in Figure 1 (a)) to create a standardized data model for a building that identifies and characterizes the "things" inside the building and the relationships between them (Balaji et al. 2016; Fierro 2021). We refer to the "things" as *entities* and relationships (*feeds*, *hasPoint*, *hasPart*) as *edges* which can be described with Brick classes. For example, a physical device that provides some service to part or all of the building can be described with the root class *Equipment* or its more specific subclasses. *Point* generally refers to *entities* that provide a source of data or control input. For example, *Sensor*, a subclass of Point, refers to the digital source of measurements, not the actual physical devices or transducers. Physical and logical spaces grouped through common characteristics (e.g. an HVAC zone) are described through the use of *Location* and its subclasses. Nameplate information, floor area size, and electrical circuit leg phase can be assigned as properties to the relevant Brick classes. A Brick data model is built up by connecting a set of two *entities* with one *edge* which is called a *triple*. Then, a collection of *triples,* which can be interconnected, makes up the graph data structure that we call the Brick data model. Figure 1 (c) shows how Brick can be used to digitally represent a hot water plant shown schematically in Figure 1 (b). A specific *triple* example based on Figure 1 (c) is DBC_Hot_Water_Loop *brick:feeds* Heat_Pump_1_1. DBC_Hot_Water_Loop and Heat_Pump_1_1 are the *entities* and *brick:feeds* is the *edge*. Additional *triples* describe what DBC_Hot_Water_Loop and Heat_Pump_1_1 are e.g. DBC_Hot_Water_Loop *rdf:type brick:Hot_Water_Loop* and Heat_Pump_1_1 *rdf:type brick:Water_Source_Heat_Pump*. The developers of the Brick ontology built it on modern Semantic Web technologies[1] typically used in the exchange of information over the internet e.g. Resource Description Framework (RDF) and Web Ontology Language (OWL). It can be integrated and linked with other Semantic Web ontologies to develop a more complete representation of the built environment and data it produces (Delgoshaei et al. 2022). This means that a Brick data model is a digital, machine-readable representation of the building and its contents that can be queried and is interoperable with a wide array of open-source and commercial software.

ASHRAE recently introduced G36 which contains standardized advanced control sequences to facilitate the implementation of high-performance HVAC controls (ASHRAE 2021). G36 solves the problem of having each design engineer develop and specify their custom control sequences. The design engineer reduces time and effort when specifying these existing sequences developed by HVAC control experts and proven to have high performance. For instance, G36 sequences for multi-zone variable air volume (VAV) systems have demonstrated average HVAC energy savings of 31% over baseline sequences (Zhang et al. 2022). However, as mentioned above, as advanced control sequences, G36 have higher complexity which may deter building stakeholders from implementing them in new or existing buildings. Also, G36 sequences are currently presented as English language specifications of controls and not the actual programming code syntax that will eventually be uploaded to the building's BAS. Control programmers still need to convert this text into computer language specific to the building's HVAC and BAS system and adapt it to the BAS point naming conventions (Butler and Veelenturf 2010). Correspondingly, control programmers may have their own interpretation of the sequences leading to various programmed G36 variants with varying field performance. The design engineer may be saving costs in specifying standardized G36 but may be shifting costs and effort to the control vendor which must program and implement the more complex G36 sequences. In addition, the higher complexity of G36 exposes themselves to more errors during the programming and implementation stages. It is at this stage where manufacturers' efforts to pre-program G36 and projects such as the OpenBuildingControl come at a great advantage. We describe the OpenBuildingControl project below.

This Brick-facilitated field demonstration employs G36 control sequences that reset the hot water supply temperature (HWST) setpoint (HWST-SP) on the building's hot water plant illustrated in Figure 1 (b). The main G36

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[1] www.w3.org/standards/semanticweb

control block of interest for this field demonstration is the trim and respond control block. The trim and respond is a demand-based reset control strategy that can control a single variable subject to multiple input sources (ASHRAE 2021). This control can be applied to reset setpoints such as pressure, temperature, and other variables. The control logic *trims* (or reduces in the case of HWST reset) the controlled setpoint at a fixed rate until the downstream equipment generates requests for higher pressure, temperature, or whatever the logic is applied. The control logic *responds* by increasing the setpoint when sufficient *requests* are generated and the cycle is repeated. We focused on the hot water system for this field demonstration because we have access to it and facility management are open to new control strategies for their building. There are significant opportunities to reduce wasted energy in this building by reducing boiler short cycling and increasing condensing mode operation. The trim and respond logic can also be applied to a chilled water system but this demonstration building has no chiller plant.

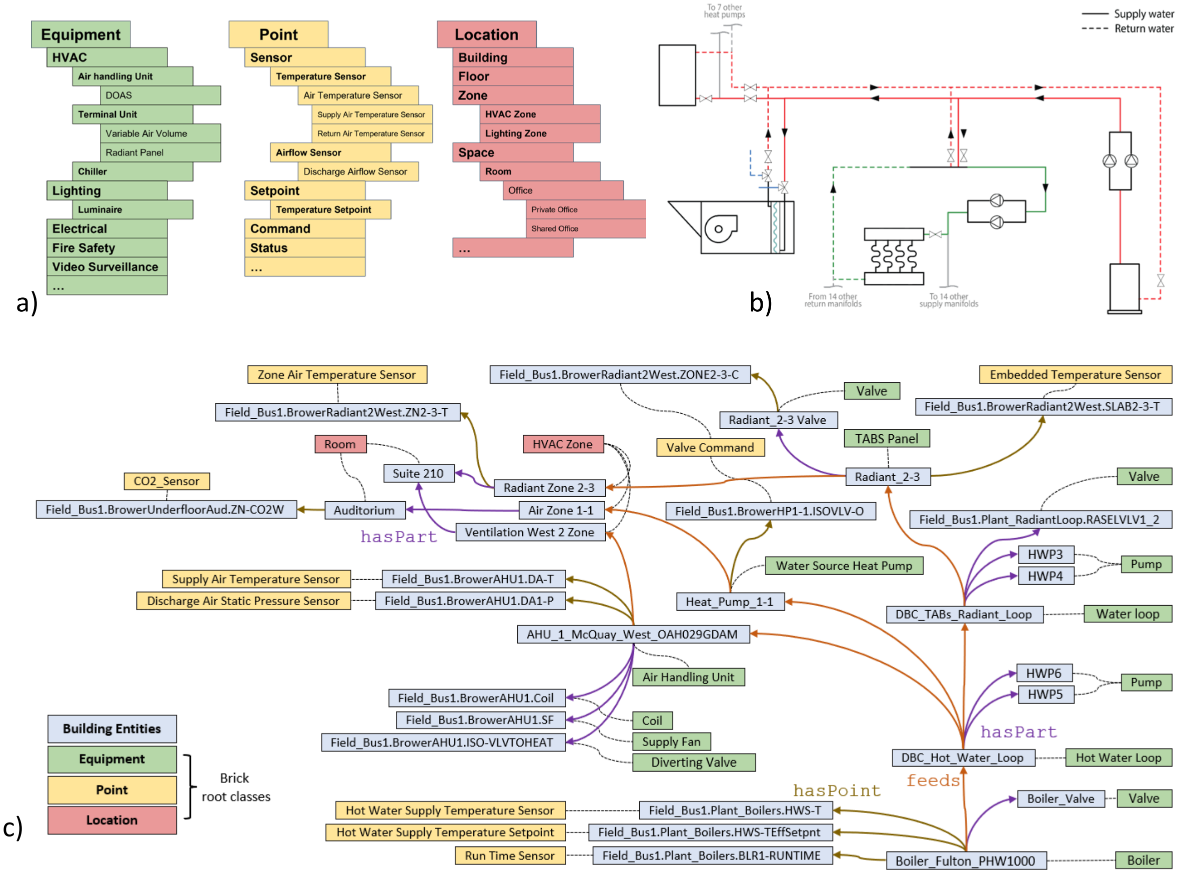

Figure 1 *(a) Excerpt of the Brick ontology class hierarchy with three root nodes: Equipment, Point, and Location (Fierro 2021). Each box represents an example of a Brick class entity with a formal definition and set of properties. (b) Schematic of the demonstration building's hot water plant. (c) Brick data model example for the hot water plant shown in (b).*

The OpenBuildingControl project aims to digitize the design, specification, deployment and verification of building control sequences such as G36 (Wetter et al. 2022). To achieve this goal, researchers in the project developed the Control Description Language (CDL), built on the equation-based modeling language called Modelica[2] , and used

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[2] modelica.org/modelicalanguage

this to express control sequences for BAS in a vendor-independent format (Wetter et al. 2019). CDL has already been used to program G36 and other high-performance HVAC control sequences and these CDL representations are currently available in the Modelica-Buildings library. The Modelica-Building library is a repository of engineering models for building energy systems and their control sequences (Wetter et al. 2014). The library provides tools and high-fidelity model components and larger system models for use in building, district energy, and control sequences simulation to enable rapid prototyping, designing and operation of an integrated system. Thus, building designers can take the standard CDL implementation of G36 to simulate the performance of the sequences on their specific buildings. CDL has also given rise to a new ASHRAE Standard 231P, whose purpose is to "define a declarative graphical programming language for building environmental control sequences that are both human and machine-readable, designed for specification, implementation through machine-to-machine translation, documentation, and simulation" (ASHRAE 2022). Consequently, the end goal is to use the same control sequence specifications and programming syntax through various stages of the building lifecycle, e.g. design, simulation, testing, deployment, and commissioning.

The CDL representation of G36 sequences can be exported as a Functional Mockup Unit (FMU), conforming to the Functional Mockup Interface (FMI) standard (Blockwitz et al. 2012). FMI was developed to allow model exchange and co-simulation of models created in different simulation environments. The FMU is a packaged file that contains details about the model parameters, variables, equations, and other relevant information to run a simulation. We exported the CDL representation of the G36 HWST reset control strategy as an FMU. The G36 HWST reset control requires signals to denote the current status of the hot water plant, whether or not it is in the staging process, the status of the pumps, the current HWST-SP, and the number of *requests* for higher hot water supply temperature. It is worth mentioning that this field demonstration was limited only to resetting the current HWST-SP and therefore a new HWST-SP was the only output from our implementation. We did not perform the full hot water plant control implementation that deals with the enable, disable, and staging control of the hot water plant's boilers and pumps which is well under the scope of G36. This was due to the pilot study nature of this field demonstration. We would have required a significant BAS overhaul to expose the necessary parameters for the full implementation of the G36 sequences on our installed PC.

APPROACH

The demonstration building is a LEED Platinum, four-story mixed-use building located in downtown Berkeley, California with about 39,000 ft^2 (3,600 m^2) of conditioned space. The building's program consists of private and open-plan offices, conference rooms, an auditorium, and a gallery. The offices are mainly located on floors two through four with a total occupancy of about 150 people. Berkeley, California has year-round moderate temperatures and is located in ASHRAE climate zone 3C. The HVAC system includes a thermally activated building (TABS) radiant system for the primary heating and cooling in the office spaces. Two air-handling units (AHU) supply 100% outdoor air to an underfloor air distribution (UFAD) system and combined with natural ventilation through operable windows provide ventilation to the building. The radiant system does not thermally condition the first floor. Instead, seven water-to-air heat pumps provide heating and cooling, and an eighth heat pump is located in a second floor conference room. The heat source for the radiant system, heat pumps, and the two AHUs for the ventilation system is provided through two gas condensing boilers with each having an input capacity of 26 Btu/hr-ft^2 (82 W/m^2). The boilers have a lead-lag operation and efficiency ranges between 85% and 95% depending on the operating mode and return water temperature when operating at or above the minimum turndown capability of the boilers.

The existing HWST reset strategy is based on the outdoor air temperature (OAT). The HWST was designed to be at 95 °F (35 °C) when OAT was at 40 °F (4.4 °C) and 75 °F (24 °C) when OAT was at 65 °F (18 °C). However, the building manager changed it to a more conservative operation (HWST=130 °F (54 °C) at OAT=55 °F (13 °C) and HWST=90 °F (32 °C) at OAT=77 °F (25 °C)) since the building manager believed the designed temperature setpoints were not high enough to maintain occupant thermal comfort during cold days. On some occasions, the building manager would override the reset operation and maintain a constant 130 °F (54 °C) HWST. We changed the radiant system control strategy based on Raftery et al. (2017) as part of an earlier study (Bauman et al. 2018) which allowed the building manager to feel more confident in reinstating an HWST reset strategy. This provided an opportunity to implement an HWST reset strategy based on G36's trim and respond control strategy. Moreover, it offered an opportunity to implement it using the various standardization projects described in the Background section above.

Among the first steps of this field demonstration was connecting a small fanless PC to the building's BAS network infrastructure, allowing us to read from and write to BACnet objects. We used the open-source project BACpypes to provide the BACnet application and network layer to establish communication for our PC to the BAS (Bender 2018). With this communication established, we performed a BACnet network scan and point list retrieval using open-source network discovery utilities such as Nmap (Nmap 2022). The BACnet point list gave us the starting point to follow a five-step process to build a Brick data model of the building. The five-step process is as follows: 1) collect siloed metadata for the building, 2) organize it into more manageable formats, 3) transform metadata into a Brick model, 4) apply inference and reasoning to the initial Brick model to discover implied information, and 5) validate the Brick model to ensure we used Brick classes and relationships correctly. We also embed BACnet object information within the Brick model and information for an external database access collecting historical data from the building's BAS. Duarte Roa et al. (2022) describe the five-step Brick model development process in more detail.

Once we developed the Brick data model, our G36 control implementation can be centered on it. At a high level, we used the building's Brick model to query and retrieve HVAC system design information and pertinent BACnet object information to obtain the HVAC's current operating status. The queried information is forwarded for further processing including forwarding it to the CDL G36 trim and respond control block to calculate a new HWST-SP. The new HWST-SP is deployed by writing it back to the hot water plant, and once again, we used Brick to retrieve the required HWST-SP BACnet object information so the boilers can use it. Figure 2 shows a schematic of the field demonstration implementation.

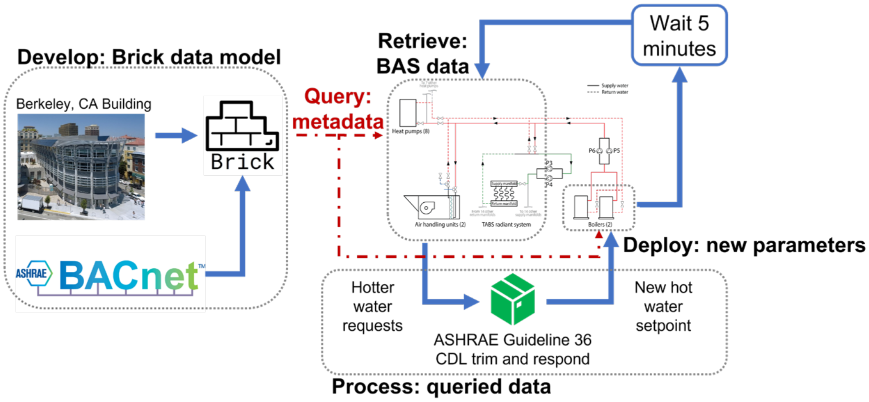

Figure 2 *Schematic of the ASHRAE Guideline 36 (G36) hot water supply temperature setpoint (HWST-SP) reset strategy implementation in a Berkeley, California building facilitated with Brick. The Brick model allows us to retrieve the hot water plant's end-users and their current operation, which is used by G36 trim and respond to calculate a new HWST-SP. The HWST-SP is written back to the BAS and the process repeats every 5 minutes.*

In our implementation, we developed generalized programmatic queries to first search the building's Brick model for the hot water plant boilers and the hot water end-users. Then, we queried each end-user to retrieve its flow control valve and pertinent BACnet object information. Once we retrieved pertinent BACnet information for the hot water end-user, we used BACpypes to send messages over BACnet to determine if the end-user is enabled and its water valve is open over 95% which formed the basis for a *request* needed for the trim and respond logic. The total sum of *requests* is sent to the FMU package containing the CDL G36 reset control to calculate a new HWST-SP. We set the total number of ignored *request*s to two, so it takes at least three *requests* for the HWST-SP to start increasing. The new HWST-SP is written back to the BAS with BACpypes using BACnet object information retrieved from the building's Brick model. The process is repeated every five minutes. We queried the Brick model for relevant metadata once at application initialization and saved query results in memory to reduce computational time in each iteration. We setup a Python 3.6 environment on our BAS connected PC with Python packages pyfmi[3], brickschema[4], asyncio[5], and other supporting packages to load, initialize, and simulate the FMU, read and query the Brick model, and setup periodic intervals to repeat the control strategy. We started running the Brick enabled G36 HWST reset control on November 30, 2021 with 130 °F (54 °C) and 90 °F (32 °C) as the upper and lower setpoint limits, respectively. These controls have been running through late March 2023.

RESULTS AND DISCUSSION

The Brick enabled G36 HWST reset control implementation performed as expected. We initiated the G36 HWST reset at a time when outdoor air temperature (OAT) averaged 49 °F (9 °C) for the whole month of December 2021 and 51 °F (10 °C) for the four days shown in Figure 3 (a). As a consequence, the number of calculated hotter water requests was above the ignored request threshold of two. The requests varied from one to five requests with an average of 2.6 request for December 2021 and 3.8 for the four-day period in Figure 3 (a). Thus, there was not much variation in the new calculated HWST-SP during the first few weeks of starting the Brick enabled controls. The HWST-SP mostly operated at the upper temperature setpoint limit we defined, as shown in Figure 3 (a). The average temperatures are 129 °F (54 °C) for the boiler supply setpoint, 133 °F (56 °C) for the hot water supply, and 121 °F (50 °C) for the hot water return for the four-day period in Figure 3 (a). There was not much difference between the existing controls strategies and the new G36 controller setpoint during these weather conditions.

However, we started to see more variation in the HWST-SP during the shoulder season months when the outdoor temperatures began to increase. In March 2022, the OAT averaged 54 °F (12 °C) for the whole month and 54 °F (12 °C) for the four days shown in Figure 3 (b). During the shoulder months, the number of requests varied from zero to five requests with an average of 2.8 requests for March 2022 and 2.7 for the four-day period in Figure 3 (b). The HWST-SP varied the full range between the upper and lower temperature limits we defined. In particular, the HWST-SP increased during occupancy hours when heat pumps' heating setpoints came out of their nighttime setbacks requesting hotter water. The average temperatures are 109 °F (43 °C) for the boiler supply setpoint, 114 °F (46 °C) for the hot water supply, and 105 °F (40 °C) for the hot water return for the four-day period in Figure 3 (b).

The more important aspect of this Brick enabled G36 control implementation is that there are no hard-coded parameters that prevent the implementation from being ported over to a new building. The Brick data model allows us to develop general programmatic queries. If we were to represent them in simple language format, the ones we used in this field demonstration would read as "Get me all the hot water end-users for the building's hot water plant" and "How many of these end-users are requesting hotter water?". The generic queries allow us to avoid using unique BAS point naming conventions as it is typically done. The only requirement for the new building is to have a Brick data model with the relevant equipment, sensors, and actuators accurately described. However, developing a Brick

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[3] pypi.org/project/PyFMI

[4] pypi.org/project/brickschema

[5] pypi.org/project/asyncio

model for an existing building may be a significant undertaking if information is not readily available (Duarte Roa et al. 2022). For this reason, it might make sense to develop a Brick model during a significant controls retrofit. Return on this investment will materialize when re-using the Brick model for more than one Brick enabled application especially if multiple third-party vendors get involved. This field demonstration of Brick enabled controls shows us a path forward where advanced control strategies for building systems can one day be as easy as installing a new application on our mobile phones.

Measurement and verification were not part of the scope for this field demonstration. The main objective of this research was to have a working software implementation that incorporates the four standardization projects mentioned in the background section above i.e. BACnet, Brick, CDL, and G36. However, we were able to access gas utility data to estimate the gas cost savings of implementing the new G36 controller for months December 2021 through April 2022. We calculated a range of 20% to 45% monthly cost savings when compared to the monthly average gas costs between those same months for the years 2017-2019 where the existing control strategy was used. Matching the boiler plant output with the demand of the hot water end-users allowed the boiler to increase efficiency during condensing mode operation. Natural gas boilers start condensing operation at a return water temperature of about 135 °F (57 °C) and their efficiency continues to increase the lower the return water temperature.

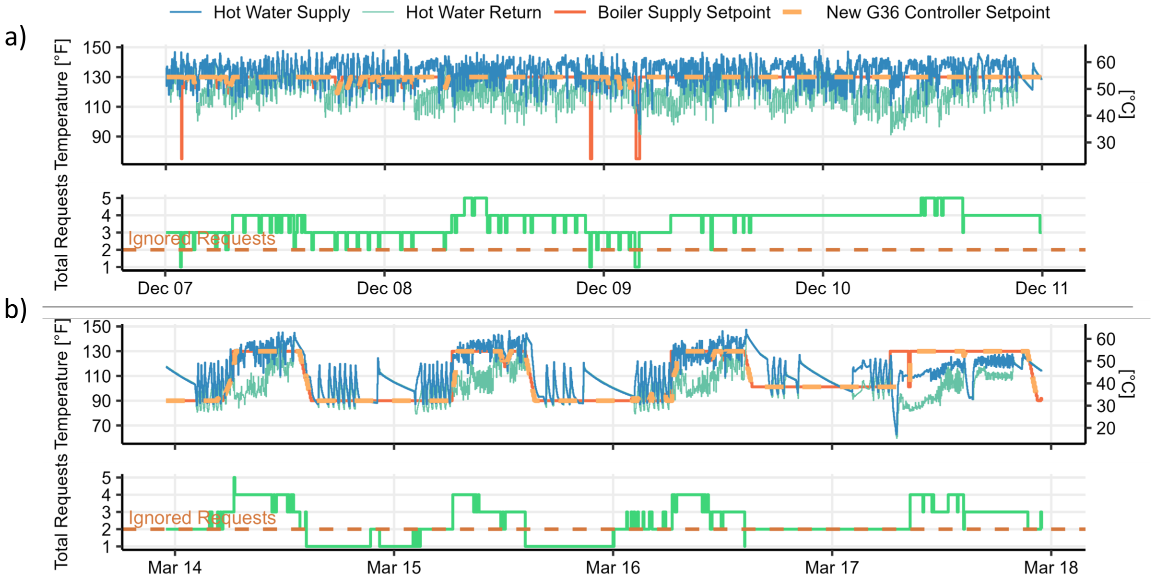

Figure 3 *Example of Brick enabled ASHRAE Guideline 36 hot water supply temperature setpoint reset strategy during the (a) winter season and (b) during shoulder season when outdoor temperatures are milder. "New G36 Controller Setpoint" refers to the new calculated setpoint by the G36 control block and "Boiler Supply Setpoint" refers to the setpoint written in the hot water plant. The hot water plant is running continuously in both seasons.*

CONCLUSION

Many advanced control sequences and algorithms are introduced every year with the promise to improve building operations that will increase energy efficiency and reduce greenhouse gas emissions. Yet, they never get deployed in buildings because each control implementation needs to be customized which hinders the widespread of advanced control sequences. In this paper, we present a field demonstration of Brick enabled ASHRAE Guideline 36

(G36) controls sequences in a Berkeley, California office building. We used four standardization projects to streamline the deployment of advanced control sequences such as G36's hot water supply temperature setpoint reset in a consistent, scalable, and portable manner that will increase the penetration rate of such control sequences. These standardization projects provide tools that standardized semantic descriptions and relationships of the building's assets and data points (Brick), standardized communication protocol to read from and write to the building's BAS (BACnet), and standardized code implementations (CDL) of standardized advanced control strategies (G36). Using these tools avoids repetitive efforts and increases available resources to focus on implementing the best energy and cost-saving applications across various buildings.

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REFERENCES

ASHRAE. 2020. *ASHRAE Standard 135 - BACnet - A data communications protocol for building automation and control networks*. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

ASHRAE. 2021. *ASHRAE Guideline 36 - High Performance Sequences of Operation for HVAC System*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2022. Standards & Guidelines: Titles, Purposes, and Scopes.

Balaji, B., A. Bhattacharya, G. Fierro, J. Gao, J. Gluck, D. Hong, A. Johansen, J. Koh, J. Ploennigs, Y. Agarwal, M. Berges, D. Culler, R. Gupta, M. B. Kjærgaard, M. Srivastava, and K. Whitehouse. 2016. Brick: Towards a Unified Metadata Schema For Buildings. In *Proceedings of the 3rd ACM International Conference on Systems for Energy-Efficient Built Environments* (pp. 41–50). Palo Alto CA USA: ACM.

Bauman, F., P. Raftery, S. Schiavon, C. Karmann, J. Pantelic, C. Duarte, J. Woolley, M. Dawe, L. Graham, D. Miller, H. Cheng, J. (Dove) Feng, D. Heinzerling, C. Higgins, K. Carbonnier, G. Paliaga, A. Pande, and F. Farahmand. 2018. *Optimizing Radiant Systems for Energy Efficiency and Comfort* (No. EPC-14-009). Sacramento, CA: California Energy Commission.

Bender, J. 2018. BACpypes Documentation.

Bergmann, H., C. Mosiman, A. Saha, S. Haile, and W. Livingood. 2020. Semantic Interoperability to Enable Smart, Grid-Interactive Efficient Buildings. In *2020 Summer Study on Energy Efficiency in Buildings* (p. 18). ACEEE.

Blockwitz, T., M. Otter, J. Akesson, M. Arnold, C. Clauss, H. Elmqvist, M. Friedrich, A. Junghanns, J. Mauss, D. Neumerkel, H. Olsson, and A. Viel. 2012. Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models (pp. 173–184). Presented at the 9th International MODELICA Conference, Munich, Germany.

Brambley, M. R., P. Haves, S. C. McDonald, P. Torcellini, D. Hansen, D. R. Holmberg, and K. W. Roth. 2005. *Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways* (No. PNNL-15149) (p. 162). Richland, Washington: Pacific Northwest National Laboratory.

Butler, J. F., and R. Veelenturf. 2010. Point Naming Standards. *ASHRAE Journal.*

Delgoshaei, P., M. Heidarinejad, and M. A. Austin. 2022. A Semantic Approach for Building System Operations: Knowledge Representation and Reasoning. *Sustainability*, *14*(10):5810.

Duarte Roa, C., P. Raftery, R. Sun, L. Paul, A. Krishnan, M. Pritoni, G. Fierro, and T. Peffer. 2022. Towards a Stronger Foundation: Digitizing Commercial Buildings with Brick to Enable Portable Advanced Applications. In *Climate Solutions: Efficiency, Equity, and Decarbonization*. Pacific Grove, CA: ACEEE.

EIA. 2012. Commercial Building Energy Consumption Survey (CBECS) Data. Energy Information Administration, U.S. Department of Energy.

EIA. 2022. Commercial Buildings Energy Consumption Survey (CBECS) Data. Energy Information Administration, U.S. Department of Energy.

Fernandez, N., S. Katipamula, W. Wang, Y. Huang, and G. Liu. 2015. Energy savings modelling of re-tuning energy conservation measures in large office buildings. *Journal of Building Performance Simulation*, *8*(6):391–407.

Fernandez, N., S. Katipamula, W. Wang, Y. Xie, M. Zhao, and C. D. Corbin. 2017. *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction* (No. PNNL-25985). Richland, Washington: Pacific Northwest National Laboratory.

Fierro, G. 2021. *Self-Adapting Software for Cyberphysical Systems* (Doctoral Dissertation). University of California, Berkeley, Berkeley, CA.

Fierro, G., J. Koh, Y. Agarwal, R. K. Gupta, and D. E. Culler. 2019. Beyond a House of Sticks: Formalizing Metadata Tags with Brick. In *Proceedings of the 6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation* (pp. 125–134). New York NY USA: ACM.

Granderson, J., and G. Lin. 2016. Building energy information systems: synthesis of costs, savings, and best-practice uses. *Energy Efficiency*, *9*(6):1369–1384.

Lin, G., H. Kramer, and J. Granderson. 2020. Building fault detection and diagnostics: Achieved savings, and methods to evaluate algorithm performance. *Building and Environment*, *168*:106505.

Nmap. 2022. Nmap: the Network Mapper - Free Security Scanner. Nmap Project.

Pritoni, M., D. Paine, G. Fierro, C. Mosiman, M. Poplawski, A. Saha, J. Bender, and J. Granderson. 2021. Metadata Schemas and Ontologies for Building Energy Applications: A Critical Review and Use Case Analysis. *Energies*, *14*(7):2024.

Project Haystack. 2023. Project Haystack Website.

Quinn, C., and J. J. McArthur. 2021. A case study comparing the completeness and expressiveness of two industry recognized ontologies. *Advanced Engineering Informatics*, *47*:101233.

Raftery, P., C. Duarte, S. Schiavon, and F. Bauman. 2017. A new control strategy for high thermal mass radiant systems. In *Proceedings of Building Simulation 2017*. San Francisco, CA: International Building Performance Simulation Association.

Wetter, M., P. Ehrlich, A. Gautier, M. Grahovac, P. Haves, J. Hu, A. Prakash, D. Robin, and K. Zhang. 2022. OpenBuildingControl: Digitizing the control delivery from building energy modeling to specification, implementation and formal verification. *Energy*, *238*:121501.

Wetter, M., M. Grahovac, and J. Hu. 2019. Control Description Language (pp. 17–26). Presented at the The American Modelica Conference 2018, October 9-10, Somberg Conference Center, Cambridge MA, USA.

Wetter, M., W. Zuo, T. S. Nouidui, and X. Pang. 2014. Modelica Buildings library. *Journal of Building Performance Simulation*, *7*(4):253–270.

Zhang, K., D. Blum, H. Cheng, G. Paliaga, M. Wetter, and J. Granderson. 2022. Estimating ASHRAE Guideline 36 energy savings for multi-zone variable air volume systems using Spawn of EnergyPlus. *Journal of Building Performance Simulation*, *15*(2):215–236.