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Open Building Operating System: an Open-Source Grid Responsive Control Platform for Buildings

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ABSTRACT

Grid-interactive efficient buildings (GEBs) with flexible loads are a promising method to decarbonize buildings, shift loads during peak hours, and lower energy use and electricity costs. Despite the promising benefits of GEBs, automation systems that manage flexible loads in response to energy prices or other grid signals are still uncommon in small and medium commercial buildings. Recent literature demonstrates such control solutions, but they often rely on custom integrations lacking the tools and drivers needed for scalability. To address these gaps, our team has created a fully open-source software stack capable of integrating heterogeneous flexible building loads and implementing integrated portable control applications called the Open Building Operating System (OpenBOS). The software can be deployed over existing control architecture with a small capital cost. OpenBOS leverages semantic models, which have been the subject of recent investigations to facilitate application portability. The use of semantic data reduces the labor and expense required to deploy and update smart control applications, increasing scalability. In this paper, the semantic modeling schema "Brick" was used, but the proposed approach can also be applied to ASHRAE standard 223P, when released. This paper describes the methodology and software components of OpenBOS and demonstrates its functionality with a rule-based demand flexibility control application configured using a semantic model. This application was tested at a real building in NY that uses a dual-fuel heating system made up of five ductless heat pump mini-splits and a central furnace serving a single zone. The demonstration reduced electricity costs at the site by 27%, demand during a shed event by 49%, and furnace usage by 35%.

INTRODUCTION

Grid-Interactive Efficient Buildings (GEBs) are buildings that combine smart systems and communication technologies to optimize energy efficiency and actively use demand flexibility while offering a comfortable and productive environment for occupants. At scale, GEBs could reduce CO2 emissions by 80 million tons per year by 2030 (Satchwell et al. 2021). An essential facet of GEBs is demand flexibility (DF), the ability to shift when loads are used within buildings. DF can be enabled by control applications that respond to event or price signals that incentivize a site to change its loads. Small- and Medium- Commercial Buildings (SMCBs) account for half of the floor area of all commercial buildings, offering significant potential for DF applications (EIA, 2021).

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In SMCBs, Internet of Things (IoT) devices such as WiFi-connected thermostats have rapidly become popular (Ford et al. 2017). They are low-cost, discrete, and can be installed with minimal disruption, which is particularly useful in SMCBs that have limited space and budget constraints. These IoT devices are often connected to vendor cloud platforms and controlled individually. Some of their potential for DF applications has been recognized and explored through aggregators or utility demand response programs that directly control WiFi-connected thermostats (Rajabi et al. 2017). However, without coordinating the IoT devices installed in a building, the full potential of DF in SMCBs cannot be realized.

Current control platform technologies, such as VOLTTRON (Katipamula et al. 2016), allow the integration of heterogeneous IoT devices within a building, however, the deployment of control applications on top of such platforms is still labor-intensive and error-prone. While a control platform may be able to handle various APIs, the metadata (semantic description) for their related data points (e.g., measurement and control points from IoT devices associated with building systems such as HVAC) is often only contained in unstructured and non-standard sources such as drawings, English language documents, and staff knowledge (Bergmann et al. 2020). This limits the discovery and interpretability of these data points, resulting in costly manual and ad-hoc point mapping processes when configuring new applications (Pritoni et al. 2021). To deploy a control application at a building, technology providers need to integrate required devices, map their data, and reprogram or reconfigure applications to use that data. Additionally, if a building owner wants to upgrade a control application or add an additional application from a different vendor, this process has to be completed again at the same cost. Since HVAC systems in SMCBs have relatively lower total energy costs, and thus less opportunity for savings, such manual and costly processes of developing and deploying control applications do not make sense economically.

OpenBOS is a new software solution that innovates upon current building control technologies to provide a scalable method for deploying control applications in SMCBs. It accomplishes this through the use of semantic models. Semantic models enable the development of applications that can be portable across various buildings and over the whole life cycle of an individual building (Fierro et al. 2020). This paper first describes the capabilities of semantic modeling. Second, it introduces OpenBOS, describing the methodology behind it and each of its software components. Finally, it demonstrates an example application, a rule-based DF control application that can be easily configured using a semantic model, and shows the results from deploying OpenBOS in a real building in New York.

SEMANTIC MODELING

Semantic models offer a structured approach to defining information, allowing buildings to be represented digitally in a consistent and standardized way (Fierro et al., 2022). These models describe information about building spaces (e.g., thermal zones), equipment (e.g., rooftop units), including their components (e.g., fans), measurement and control points (e.g., sensors and setpoints), and the relationship between them. The models are represented by graphs and can be queried to extract knowledge in a machine-readable format. By querying semantic models, software tools, such as OpenBOS, can determine the meaning of available measurement or control points and their association with spaces and equipment using common descriptions. This allows for the seamless integration of data from various vendors and the definition of replicable, semi-automated application configuration processes (Roth et al. 2022). The latter helps applications to be portable across different buildings without extensive reprogramming. This is beneficial in SMCBs, where heterogeneous IoT devices with diverse naming conventions and data acquisition procedures are commonly deployed, and the deployment of control applications needs to be low cost.

The potential of portable applications using semantic models has been demonstrated by MORTAR, an open-source platform containing semantic models for over 90 buildings that allows analytics applications to query semantic models for configuration over multiple buildings (Fierro et al. 2018). However, real-world demonstrations of semantics-driven control applications are scarce in the literature. As such, this paper aims to introduce and demonstrate the use of semantic models with OpenBOS to enable semi-automated configuration of portable control applications. Brick is the semantic modeling schema currently used by OpenBOS. Brick is an open-source semantic modeling schema that uses semantic web technologies to describe the physical, logical, and virtual assets in a building and their relationships in a machine-readable, uniform, and interoperable way (Roa et al. 2022). Brick semantic models contain a digital representation of each data source in a building, such as sensors or setpoints, as well as their relationships to the equipment and locations (e.g., what zone a sensor is measuring, or which equipment a setpoint belongs to). A Brick model is thus able to provide a consistent representation of building systems and their data, which can be relevant to a wide array of control applications. Brick models usually do not include telemetry data about real-time or historical building system operations, but they point to other data sources (e.g., time series database, BMS/IoT gateway, or other digital storage) that applications can use to retrieve data or write new commands. Although OpenBOS employs Brick, other similar semantic schemas can be included in the future, such as ASHRAE Standard 223P (ASHRAE 2018), which aims to model building systems in greater detail but is currently still under development.

OPENBOS SOFTWARE

OpenBOS is a software solution that utilizes semantic models to enable the deployment of portable control applications (Figure 1). All of OpenBOS's components are open-source and completely free to use and can be easily replicated at other buildings. OpenBOS architecture contains three layers. The top layer includes portable applications, as well as a data dashboard for monitoring and analysis. The middle layer of the architecture includes the middleware. The middleware platform used is VOLTTRON, which securely connects the applications to the building and external data sources, handling the required read and write commands for control application logic. Drivers are parts of the middleware which manage communication to specific pieces of hardware and external data sources. The semantic model and database have also been included in this layer. The bottom layer contains the building measurement and control points (hardware) that are being controlled, and external data sources that are used by the applications. This section describes the proposed methodology for the deployment of portable applications within OpenBOS and each component of its architecture.

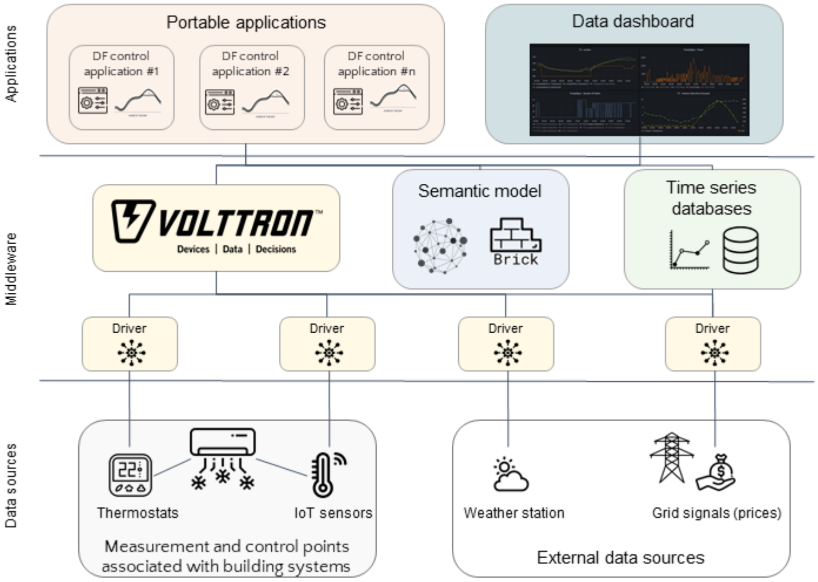

Figure 1 Components of OpenBOS architecture

The proposed methodology for enabling OpenBOS to deploy portable DF control applications through semantic models consists of four steps (Figure 2). First, a portable application is created. The application must be generalizable across heterogeneous buildings, which means that it cannot be hard-coded for a specific building. Second, a Brick semantic model must be created for a given building. The model should describe the metadata about the building systems and measurement/control points, as well as pointers to their respective sources, from where data can be read and written (e.g., time series databases and control points via the middleware drivers). Third, the portable application is semi-automatically configured by extracting required pointers and other metadata through automated semantic queries bundled with the application. Certain applications may require a limited amount of information that is not in the Brick model, such as occupant comfort constraints or price signals. Finally, the application is executed, utilizing the middleware for data reading and writing.

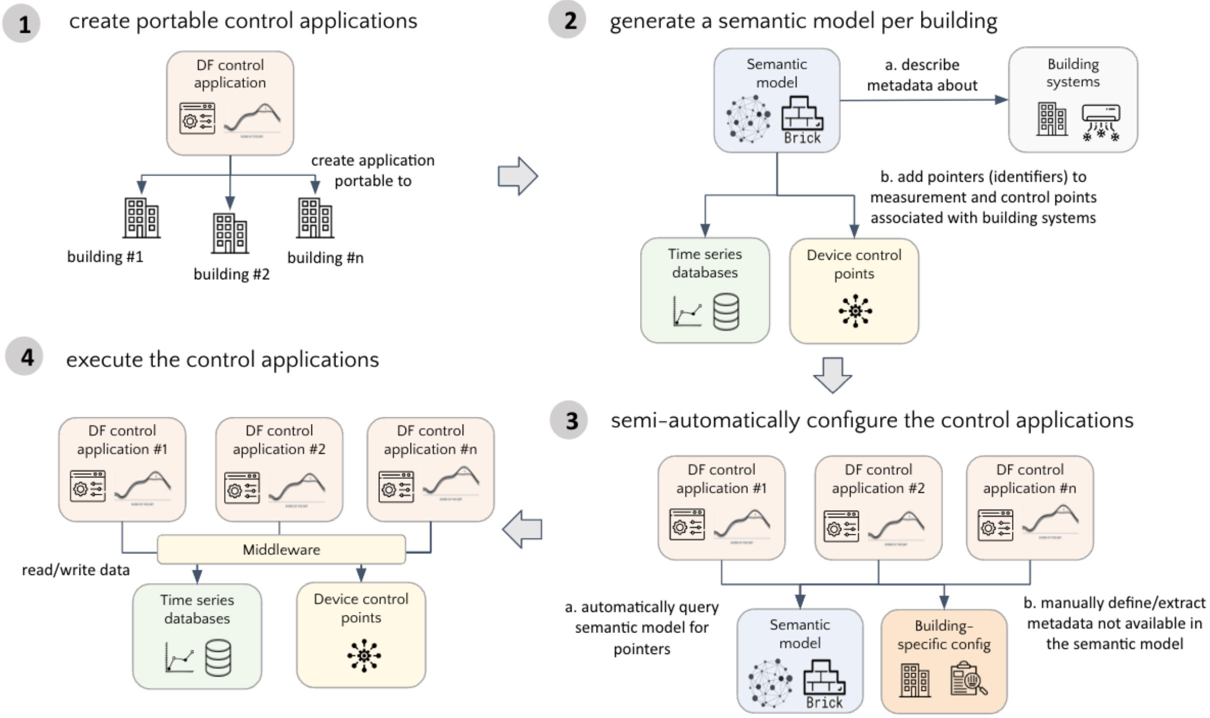

Figure 2 The proposed methodology for enabling OpenBOS to deploy portable DF applications leveraging semantic models and middleware**.**

While the first step is relevant from the perspective of application developers, who can more easily reuse developed control applications across many buildings, the last three are important from the perspective of building owners/operators, who can reuse the same semantic model for a given building to facilitate and reduce costs for the deployment of several applications.

Portable Applications

OpenBOS portable applications contain supervisory control logic that can run on many buildings without extensive reprogramming. Along with the semantic model used for automated configuration, the OpenBOS middleware abstracts the specific protocols and data structures used to communicate with the diverse building devices and external data sources. This allows portable applications to exclusively contain logic, with no communication details, enabling them to run on various applicable systems. It is important to note that although portable applications are intended to run across various heterogeneous buildings, certain applications may be more suitable for given building systems.

Semantic Model

The OpenBOS software solution requires the creation of Brick semantic models for specific buildings. For that, OpenBOS leverages BuildingMOTIF (Fierro et al. 2022), a toolset that helps to create Brick models following a well-defined workflow process that ensures they are constructed correctly and are able to run applications. The created Brick model includes building thermal zones, HVAC systems and their measurement and control points, as well as the relationships between all of them. While the created model does not include telemetry (real-time or historical) data related to the operation of the building systems, it does provide their meaning and context, as well as their addressing information (i.e., pointers to where to find and query them via the OpenBOS middleware drivers and database). The model is then used by OpenBOS to query these pointers in order to configure the application. While the semantic model acts as the informational interface between applications and hardware, the middleware acts as the communication interface.

Middleware and Drivers

VOLTTRON (Katipamula et al. 2016) is the middleware platform used in OpenBOS. VOLTTRON handles data capture and retrieval, and provides secure management and communication between the other components of OpenBOS. It uses an agent-based approach that allows one to easily create new drivers to integrate diverse types of devices and external data sources.

Drivers connect the middleware to devices and provide a uniform interface for scalable device integration and control. VOLTTRON has existing drivers for common protocols, such as BACnet and Modbus. IoT devices that communicate via HTTP API frequently include software development kits that can be adapted into new device drivers. The communication protocols supported and the ability to develop new drivers for IoT devices allows for the integration of systems typical of SMCBs. Semantic models augment the capabilities of this approach, seamlessly integrating applications with diverse new devices with minimal manual effort.

To handle cybersecurity concerns driven by the open-source aspect of VOLTTRON, detailed threat profiles have been published for its current version, describing possible vulnerabilities and mitigation measures for deployments (Himes et al. 2021). Many threat types are considered, including denial of service, elevation of privilege, spoofing, and tampering. The mitigation strategies follow standard security procedures released by the National Institute of Standards and Technology (NIST) in SP 800-53 Rev. 5, Security and Privacy Controls for Information Systems and Organizations (Joint Task Force 2020). Some of these mitigation strategies are implemented within the middleware code, such as input validation to make sure that messages received by the middleware are not a threat. Others must be undertaken when deploying the platform, such as setting up a firewall to restrict access to the platform and database.

Database and Monitoring Dashboard

OpenBOS currently uses a Timescale database to handle the time-series data storage. Timescale is an open-source extension to PostgreSQL that is a relational database built to handle large amounts of time-series data (Timescale 2023). As for data monitoring and analysis, OpenBOS leverages the open-source dashboard Grafana

(Chakraborty and Kundan 2021). Grafana has flexible alerting capabilities and can be used to create interactive and dynamic dashboards by querying and transforming data from an attached database and then displaying it in a matrix of panels.

DEMONSTRATION

This section details the deployment of a DF portable control application with OpenBOS in a real building in New York. First, it describes the building, its systems, and baseline controls. Then, it presents the proposed rule-based DF control for load shifting and shedding and discusses the results.

Building Description

The demonstration of the proposed semantics-driven control application within OpenBOS took place at a real small office building in New York over a four-day period during March 2023. The demonstration site consists of a single zone of 3,780 ft^2 (351.2m^2) of office space served by a dual-fuel heating system of five ductless heat pumps (HPs) and one attic-mounted gas furnace (GF). The ductless HPs had inaccessible internal thermostats, and required infrared (IR) remotes to change their setpoints or operating mode. Thus, WiFi-enabled IR remotes with built-in temperature sensors were used to monitor the space and change the setpoints of the HPs. The electrical loads of each HP were measured minutely by a WiFi-enabled electricity meter, and the GF was controlled by a standard WiFi-enabled thermostat. All of these devices were connected to the internet by a 4G cellular router. Individual drivers were created for each device to integrate them into OpenBOS, and they were controlled via vendor cloud APIs.

Baseline Controls

The baseline control scenario was a schedule-based setpoint operation, with the gas furnace operated using "droop" control. This means that the gas furnace was given a lower heating setpoint than the HPs to prevent it from operating when the HPs were able to provide sufficient heating. This scenario is the current standard method for controlling dual-fuel systems made up of units with independent thermostats. During the occupied period (7:00 AM - 8:00 PM), the HPs had a heating setpoint of 70°F (21°C), and the GF had a heating setpoint of 68°F (20°C). During the unoccupied period, all systems operated with a heating setpoint of 60.8°F (16°C). The HPs were put into heat mode because this test occurred during winter. Information about the devices and baseline control strategy for the site is summarized in Table 1.

Table 1. Building Summary

	Details
Baseline Control Strategy	Occupied: Indoor Heating Temperature Setpoint 70°F (21°C) from 7:00 AM - 08:00 PM Unoccupied: Indoor Heating Temperature Setpoint 60°F (16°C) at all other times
Electricity Cost (conEdison ToU small business[1])	7:00 AM - 10:00 PM: On-peak (18.62$/kWh). Other times: Off-peak (1.38$/kWh)

OpenBOS DF Control Application

The proposed application introduces a rule-based control scheme for DF that allows for individual control of packaged HVAC units to shift electrical loads to earlier in the day. It was designed to be portable and run effectively on the packaged units with zone-level thermostats that are common in SMCBs. For this purpose, the deployment of the application started with an initialization routine to semi-automatically configure the control application with

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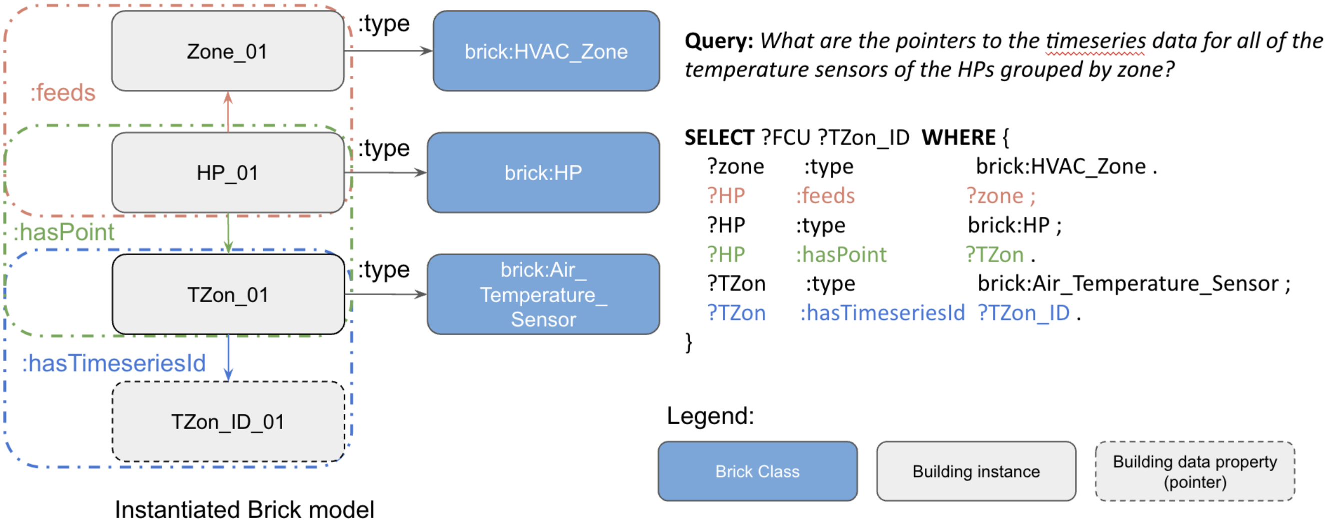
[1] https://www.coned.com/en/accounts-billing/your-bill/time-of-use

building-specific information. In this process, the semantic model created for the building was queried to retrieve the pointers to access the required data for the application, as illustrated in Figure 3 for zone temperature sensors. The application was also configured with additional data not available in the model, such as occupant comfort boundaries. Following this configuration process, the control was executed.



Query: *What are the pointers to the timeseries data for all of the temperature sensors of the HPs grouped by zone?*

```
SELECT ?FCU ?TZon_ID  WHERE {
  ?zone      :type               brick:HVAC_Zone .
  ?HP       :feeds              ?zone ;
  ?HP       :type               brick:HP ;
  ?HP       :hasPoint           ?TZon .
  ?TZon      :type              brick:Air_Temperature_Sensor ;
  ?TZon      :hasTimeseriesId  ?TZon_ID .
}
```

Figure 3 Snippet of the Brick model of the building and example of a query to retrieve the pointers to temperature sensors needed for the DF control application.

The control flow started by checking runaway conditions through the monitoring of the current temperatures in the zones against a predefined comfort range. If temperatures were outside of the predefined comfort range, the control application would revert to the baseline control strategy. This was followed by shift and shed event checks triggered by occupancy, electricity price, or DF event signals indicating potential grid stress conditions. The shift strategy involved preheating the building to its maximum comfort bound by a configurable amount of time before the shed event. This increases electrical loads and stores thermal energy in the building. The shed strategy involved reducing zone temperature setpoints when the building was occupied and the price exceeded a threshold, or there was a shed event signal. This decreases electrical loads. Additionally, logic was used to rotate the operation of different units to avoid simultaneous demand peaks. This logic was based on priority levels assigned to each unit depending on the difference between their monitored temperature and setpoint, and their inactive period.

In this demonstration, the DF control application managed all five HP units and the GF installed at this site. During the preheating strategy, the HP units were used in order to reduce furnace runtime. In order to maintain occupant comfort while reducing energy consumption, the control used conservative maximum and minimum comfort bounds of 71.6°F (22°C) and 66.2 °F (19°C), and a 2-hour period to preheat before a shed event. The site was sent a simulated shed event from 7:00 - 9:00 AM, when winter heating loads in NY caused a demand peak (National Grid, 2023). The existing occupancy schedule (7:00 AM - 8:00 PM) was used, and when a shift or shed event was not identified, the baseline setpoints were used.

Results

The performance of the DF control application is evaluated based on the daily amount of load it was able to shift from all the HP units, electricity cost savings, change in peak power, and furnace run-time reduction. Load shifting is represented by two metrics, the percent change of load during the preheating period and the percent change of load during the shed period. The percent change in peak power refers to the difference in the total peak from all HPs at any time during the simulated morning peak period. As shown in Table 2, the results indicate an increase in flexibility, with a load increase of 117% during the shift (preheating) period, and a load decrease of 49% during the shed period. While executing demand flexibility, the energy costs were reduced by 27%, and furnace runtime was reduced by 35%, however, there was an increase of 3% in the maximum power during the simulated morning peak period. This may have been due to the HPs not staggering operation as expected, which is a result of the use of one-way IoT IR remotes for control that did not allow the real state of the HPs to be accurately determined and controlled.

Table 2. Performance comparison between baseline and the semantics-driven DF control application

Performance metrics	Daily baseline	Daily DF	Percent Change
Load during preheat (kWh) (05:00 - 07:00)	0.432	0.940	117%
Load during shed (kWh) (07:00 - 09:00)	1.193	0.610	-49%
Electricity consumption cost ($/day)	65.541	47.582	-27%
Peak power during shed (kW) (07:00 - 09:00)	6.29	6.471	3%
Furnace Runtime (Hrs/day)	0.53	0.34	-35%

CONCLUSION

This paper describes the development of OpenBOS and demonstrates its potential to deploy semantics-driven portable control applications in SMCBs. OpenBOS was deployed in a real small office building in New York and demonstrated with a rule-based portable demand flexibility control application. In this demonstration, OpenBOS and the control application were able to reduce electricity costs at the site by 27%, demand during a shed event by 49%, and furnace usage by 35%. This demonstration serves as a concrete example of the proposed semantics-driven approach. OpenBOS was able to successfully perform demand flexibility strategies using a control application with generalizable logic that did not require manual modification to map the application to the specific data points at the site. Instead, it took advantage of the proposed automated configuration using a Brick model and semantic queries, resulting in a more streamlined configuration process with minimal manual inputs. This successful deployment of OpenBOS and the portable control application highlights the potential for significant cost and time savings in the deployment and operation of demand flexibility strategies across multiple buildings.

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