Digitizing Today's Buildings in the Real World: Lessons from Field Demonstrations

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ABSTRACT

Digital twins, created by generating a virtual replica of a building, enable safe evaluation of operational scenarios and applications like fault detection and diagnosis and advanced controls. However, a prerequisite is the creation of a machine-readable digital representation of a building, currently hindered by fragmented information scattered across mechanical drawings, point lists, and natural language sequences. As a result, digital twin development remains labor-intensive, error-prone, and difficult to validate. To address these challenges, two efforts from ASHRAE aim to support the digitalization of buildings. ASHRAE s223 establishes a semantic model of buildings, representing system components, configuration, and data sources. ASHRAE s231 defines a vendor-neutral programming language for expressing their control logic. As the industry evaluates implementing them in their products, understanding the challenges that vendors and implementers may face is crucial.

In this paper, we present findings and lessons learned from field demonstrations in five buildings that implemented control applications using ASHRAE s223 and s231. The demonstrations highlight how semantic modeling and formalized control descriptions can significantly reduce software development time, manual point mapping, and hard-coding. Beyond time efficiency, they enable reliable automation by minimizing human interpretation and providing a means for consistency across projects. We describe the processes and best practices for model creation and model usage, from translating heterogeneous building documentation into semantic representations to implementing control logic in real-world systems. Finally, we discuss the challenges that persist, including integration with legacy software environments, gaps in interoperability, and the level of expertise still required to effectively leverage semantic models.

Introduction

The commercial buildings sector represents a significant and largely untapped opportunity for energy efficiency and grid flexibility. Building owners and operators could install energy management information systems (EMIS), advanced controls, and fault detection tools. Yet deployment of any of these is expensive and time-consuming, not because the algorithms are hard, but because the setup is: extracting point lists from heterogeneous sources (mechanical drawings, building automation system (BAS) databases, sensor tags), mapping those points across systems, translating them into application-specific formats, and validating the mappings to ensure they're correct. This labor-intensive process is driven by a fundamental problem: buildings lack a unified, machine-readable representation that can be reliably shared across tools and applications. Instead, information is scattered across mechanical drawings, point lists, and natural language sequences: each capturing some aspect of a building, but none providing a form that machines can reason over or systems can reliably interpret (Bergmann et al. 2020; Pritoni et al. 2021). The result is that retrofitting controls, deploying an EMIS, or retrofitting a control sequence for an existing building requires substantial manual effort. Point mapping alone can consume tens to hundreds of hours. Incompatibilities between systems force expensive workarounds. Vendor lock-in persists because a building's data is locked into one system's proprietary schema, preventing competitive upgrades or tool switching. Even when high-performance control sequences, such as ASHRAE Guideline 36, (ASHRAE 2021) are available, translating them into working code for a specific building remains a bespoke, error-prone task (Wetter et al. 2022).

Two ASHRAE efforts aim to close this gap. ASHRAE s223 (ASHRAE 2026a) (s223), establishes a semantic ontology for buildings, grounding equipment, system configuration, and data sources in a linked data framework. ASHRAE s231 (ASHRAE 2026b) (s231), defines a vendor-neutral control description language (CDL) for expressing supervisory and advanced control logic in a formal, executable notation. Together, they represent a coherent approach to digitizing buildings at both the physical and logical layers (Pritoni et al. 2024).

Since they are in the early stages of adoption, questions remain about their practical applicability. How difficult are they to apply across different building types and use cases? What tooling gaps exist? How much expert knowledge is required? And critically: do the benefits - reduced configuration time, improved portability, automated validation - justify the investment from diverse stakeholders, including building operators, system integrators, and controls vendors, to create and maintain s223 semantic models and CDL-based control sequences for both new and existing buildings? This paper addresses these questions by reporting on field demonstrations conducted across five buildings in California, spanning small libraries to large university laboratory complexes. Each demonstration implemented real control applications, including Model Predictive Control (MPC), rule-based supervisory control following G36, and demand flexibility sequences, using s223 semantic models to configure those applications. Our findings document where they delivered measurable value and where significant challenges persist.

The rest of this paper proceeds as follows. First, we provide background and related work. Next, we describe the tooling ecosystem for semantic model creation and use. Then, we present the field demonstration program, including site overviews, workflows, results, and lessons learned. Finally, we conclude with recommendations for best practices and future research.

Background

ASHRAE s223: Semantic Modeling of Building Systems

s223 defines an interoperable data ontology for building systems based on the Resource Description Framework (RDF[1]) and Web Ontology Language (OWL[2]). A semantic ontology for building systems, such as s223, consists of machine-readable software code that not only provides context (such as units) of building system data, but also describes relationships of how physical equipment (such as air handlers, chillers, heat pumps and terminal units), measurement and control points (like sensors, actuators and setpoints), duct and pipe networks, and spatial structure (zones, floors) are interconnected in a building.

[1] https://www.w3.org/RDF/

[2] https://www.w3.org/OWL/

Compared to earlier building ontologies such as Brick Schema (Balaji et al. 2016), s223 takes a more detailed and prescriptive approach. It employs constraints using SHACL[3] (Shapes Constraint Language) that can be machine-validated, requiring modelers to explicitly specify connection points, flow directions, and medium types. This rigor enables automated validation and reasoning, but also increases the learning curve for practitioners familiar with less complex ontologies. The ontology is managed by ASHRAE and is expected to be published by the end of 2026. Tools to support it, including BuildingMOTIF for template-based model creation (Fierro et al. 2022) and si-builder[4] for construction from structured data, are under active development, largely as open-source software.

ASHRAE s231: Control Description Language

s231 Control Description Language (CDL), is a declarative programming language for building control sequences. CDL, a subset of the Modelica (Modelica Association 2021) modeling language, enables control logic to be written in a vendor-neutral form, supporting evaluations of these sequences both in open-loop and closed-loop. and then deployed across different BAS platforms through platform-specific translators. s231 can be used to develop control sequences for large buildings, creating machine readable software code from natural language specifications such as ASHRAE Guideline 36 and providing a library of reusable control blocks.

There are multiple pathways CDL sequences can be executed and imported into existing BAS. s231 (ASHRAE 2026b) also specifies the Control eXchange Format (CXF), a representation of CDL in a JSON format that is intended to be used as an intermediate format when importing CDL to a BAS platform. Another pathway for CDL execution involves packaging the sequences as Functional Mock-up Units (FMUs) for co-simulation or deployment, enabling integration with third-party simulation and control platforms (FMI 2021). In the field demonstrations described in this paper, CDL-based sequences were deployed through FMU wrappers connected to building automation systems via BACnet, providing a pathway from standardized control specification to real-world execution.

Related Work

The use of semantic models to configure building control applications has been explored in prior work, primarily using the Brick Schema ontology. Studies have demonstrated automated point mapping, fault detection configuration, and analytics pipeline generation from Brick models (Fierro et al. 2019; Balaji et al. 2016). A critical review of metadata schemas and ontologies for building energy applications concluded that while multiple schemas exist, none had achieved broad adoption due to fragmentation and the absence of adequate tooling (Pritoni et al. 2021). Critically, a recent demonstration at Department of Defense facilities found that software-assisted, semi-automated workflows leveraging semantic metadata have been able to significantly accelerate application setup, yielding payback periods of less than one year for control and FDD applications (Saha et al. 2025). The formal validation capabilities and connection modeling introduced by s223 represent a significant expansion of what can be expressed and checked automatically compared to earlier ontologies. Prior work with CDL has demonstrated simulation-

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[3] https://www.w3.org/TR/shacl/

[4] https://docs.open223.info/other-resources/#tools-for-working-with-ashrae-223p

based validation and performance evaluation of control sequences (Zhang et al. 2022, Wetter et al. 2022) and prototyped translation from CDL to a BAS platform (Wetter et al. 2022; Pritoni et al 2026) and from CDL to PLC (Walther et al. 2025). However, field deployment experience across diverse real buildings remains limited. This paper addresses the lack of practical demonstrations by documenting end-to-end workflows from model creation through application deployment across five buildings.

Software Tools Developed and Used

A key advantage of grounding s223 and s231 in existing ASHRAE ecosystems is that practitioners can leverage mature, well-established tooling rather than proprietary implementations (Pritoni et al. 2024). s223, built on RDF and OWL, immediately places building models within the semantic web ecosystem. Rather than requiring purpose-built query engines, models can be queried using SPARQL[5] query language, validated with SHACL (Shapes Constraint Language), and reasoned over using OWL inference. This foundation enables investments in s223 tooling to build on mature, open-source infrastructure: RDFLib[6], pyshacl[7], rdfox[8] and graph stores like Oxigraph[9] and Apache Jena[10] are all well-maintained and production-ready components, not innovations required solely for buildings. Similarly, s231 is based on Modelica, a widely used open-source modeling language with established compilers, IDEs, and simulation environments. Control sequences authored in CDL can be compiled, simulated, and exported as Functional Mock-up Units (FMUs), a standardized format for exchanging models across tools, using the existing Modelica and FMI (Functional Mock-up Interface) ecosystems. This design avoids vendor lock-in and enables CDL sequences to be validated in simulation before deployment and then integrated with any FMU-compatible platform. The tools (summarized in Table 1) described below are built on these mature ecosystems and were used in the demonstrations.

s223 Model Creation

- **BuildingMOTIF** is a Python library for template-based semantic model creation and validation. Templates encode the expected structure of common building components as parameterized RDF patterns; instantiation populates instance-specific values and automatically assembles compliant s223 graphs. BuildingMOTIF generates SHACL shapes for validation, enabling interactive quality checks during modeling.
- **si-builder** is a Python toolkit for constructing s223 models programmatically from structured data sources (BACnet scans, point lists, equipment schedules). It provides a higher-level API over raw RDF libraries, supporting large-scale model generation with automated element naming.

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5 https://www.w3.org/TR/sparql11-query/
6 https://rdflib.readthedocs.io/
7 https://pypi.org/project/pyshacl
8 https://www.oxfordsemantic.tech/rdfox
9 https://github.com/oxigraph/oxigraph
10 https://jena.apache.org/

- **SemanticModelBuilder** is a python package that leverages survey-based workflows to lower the barrier for non-expert users. A SurveyGenerator[11] module produces a pre-filled spreadsheet survey from simplified building topology descriptions and then the SurveyReader module converts completed surveys into s223 models using BuildingMOTIF.

s223 Model Querying & Retrieval

- **DFLEXLIBS** is a Python demand flexibility control library that retrieves data via SHACL-validated SPARQL queries against s223 models rather than hard-coding point names, enabling the same sequence code to deploy across different buildings without modification.
- **b-schema and Oxigraph** address performance scaling. b-schema (Paul et al. 2025a) provides a simplified building-specific schema derived from s223 templates for faster querying; Oxigraph with tq-shacl[12] substantially improves SHACL validation and SPARQL execution speed on large models (>100,000 triples).

s231 Sequence Creation, Simulation and Compilation

- **Dymola[13]** is a commercial Modelica IDE used to author CDL control sequences, validate them through simulation, and export production-ready FMUs for deployment across heterogeneous BAS platforms. Open-source alternatives like OpenModelica provide equivalent FMU export at no cost.
- **PyFMI[14]** is a Python package that loads and executes FMUs in real-time or batch mode. It can be used for model-in-the-loop control of building equipment or for offline testing of sequences against recorded building data.

Table 1. Overview of the tools used in the demonstrations.

Tool	Inputs (for the field demonstrations)	Outputs
BuildingMOTIF	Templates; equipment names, BACnet network scans, zone data	s223 model
si-builder	BACnet network scans; point lists; equipment schedule	s223 model
SemanticModel Builder	Survey spreadsheet: building topology, equipment type	s223 model
DFLEXLIBS	s223 semantic models; sensor data	HVAC setpoints
Dymola	Modelica Buildings Library (including s231 CDL)	CDL sequence and FMUs

[11] https://github.com/lazlop/SemanticModelBuilder
[12] https://pypi.org/project/brick-tq-shacl/
[13] https://www.3ds.com/products/catia/dymola
[14] https://github.com/modelon-community/PyFMI

PyFMI	FMU	HVAC setpoints

Field Demonstrations

Five buildings were selected for the field demonstrations to span a range of building types, sizes, mechanical systems, and use cases. Table 2 summarizes the sites, and Figure 1 shows the buildings.

Table 2. Overview of the field demonstration sites and applications.

Building	Type	Application	Size ft²	Tools Used	References
B1	Office+ Lab	Rule-based G36 supervisory control (chilled & hot water setpoint reset)	141,000	BuildingMOTIF, Dymola, PyFMI	(Jayarathne et al. 2026)
B2	Office	Supervisory MPC of VRF system	6,777	DFLEXLIBS	(Casillas et al. 2026, Paul et al. 2025b)
B3	Office	Rule-based G36 supervisory control of boiler plant (hot water setpoint reset)	38,600	BuildingMOTIF, Dymola, PyFMI	(Jayarathne et al. 2026)
B4	Library	Supervisory MPC of HP-RTU	7,275	BuildingMOTIF, si-builder, SemanticModelBuilder	(Casillas et al. 2026, Paul et al. 2025b)
B5	Office	Supervisory MPC of RTUs and UFAD	65,000	BuildingMOTIF, si-builder	(Zanetti et al. 2026)

Sites and Applications Overview

- **B1** is a seven-story, 141,000 ft² university research building in California (ASHRAE Climate Zone 3C), housing fabrication and robotics laboratories, Class 100 and 1000 cleanrooms, offices, and classrooms. It is served by a Siemens Apogee/Desigo BAS, two primary air handling units (one all-air VAV system for offices, one 100% outside-air system for laboratory spaces), absorption and centrifugal chillers, and a campus steam heating system. In **B1**, G36 trim-and-respond sequences were deployed for chilled water and hot water setpoint reset, packaged as s231 CDL FMUs and deployed via BACnet. A key research focus was demonstrating implementation benefits: rather than re-programming control logic for B3, we deployed the same CDL sequences developed and validated at B1, even across different BAS platforms (Siemens at B1, Johnson Controls at B3).

Figure 1. The five field demonstration sites.

- **B2** is a 6,777 ft^2 single-story office and research building in California (ASHRAE Climate Zone 3B) with 13 zones served by a Daikin Variable Refrigerant Flow (VRF) system comprising two outdoor units and 14 fan coil units, supplemented by a dedicated outdoor air system. Two applications were demonstrated: supervisory MPC for load shifting and cost reduction, and portable demand flexibility sequences from the DFLEXLIBS library, reusing the same s223 model for both.
- **B3** is a four-story, 42,000 ft^2 (only 38,600 ft^2 is conditioned) LEED Platinum certified office building in California (ASHRAE Climate Zone 3C) managed by a Johnson Controls Metasys BAS, featuring a 68 kW photovoltaic array. The application demonstrated was G36 trim-and-response control of the boiler plant for hot water temperature setpoint reset. Critically, the s231 CDL sequences and SPARQL queries developed and validated at B1 were redeployed at B3 without changes to the software pipeline, in spite of having two different BAS platforms.
- **B4** is a 7,275 ft^2 single-story county library in California (ASHRAE Climate Zone 3B), maintained by Los Angeles County with no dedicated facilities manager. It is served by a 20-ton and a 5-ton Carrier heat pump rooftop unit (HP-RTU) communicating via BACnet MS/TP. The application being demonstrated was a supervisory MPC of the HP-RTU. The demonstration also validated a full survey-based workflow for semantic model creation, and measured the time savings from semantic modeling relative to the manual baseline.
- **B5** is a four-story building in California (ASHRAE Climate Zone 3C), where the study focused on the HVAC system serving the third and fourth floor office spaces, constituting approximately 65,000 ft^2, and thermally decoupled from the first two floors by insulation. The focus area is served by an Automated Logic Control BAS controlling a multizone underfloor air distribution (UFAD) system served by four RTUs. The application was supervisory MPC of the RTUs and terminal units of the UFAD system, with a focus on quantifying how semantic modeling reduces MPC configuration effort and handles heterogeneous point naming conventions.

Evaluation Approach

For B1 and B3, baseline control maintained fixed water supply setpoints (chilled water 43°F and hot water 190°F at B1; hot water 130°F at B3); weather-normalized annual energy consumption was estimated using Time-of-Week and Temperature (TOWT) regression models with TMY3 data, employing IPMVP Option B (retrofit isolation) for chilled and hot water thermal energy and IPMVP Option C (whole facility) for B3's natural gas; measurements included directly measured thermal energy and electrical consumption via flow rates and power meters, with reported values representing normalized annual estimates. For B2 and B4, baseline control used existing building automation schedules with rapid M&V methodology, alternating daily between baseline and MPC operation; results are measured values (not normalized), compared under comparable daily weather conditions using regression against mean outdoor air temperature; cost savings reflect dynamic electricity pricing signals that changed hourly throughout each test period. For B5, baseline control used occupancy-based schedules with RTUs off during unoccupied hours (weekdays 5am–10pm), zone setpoints heating 21°C occupied/19°C unoccupied and cooling 23°C occupied/26°C unoccupied; the 2025 summer test employed dynamic electricity prices that changed hourly with different daily profiles repeating weekly; reported cost savings are measured values from the 11-day test period, compared under comparable weather via daily mean outdoor air temperature regression.

Results

All five sites successfully deployed their target applications. Table 3 summarizes the quantitative outcomes.

Table 3. Summary of application results across demonstration sites

Building	Application	Key Results
B1	G36 chiller + boiler plant control	~14.6% annual chiller electricity reduction; ~\$17,334/yr cost savings (\$0.12/ft²); ~11.5% hot water thermal energy reduction; ~\$23,860/yr gas savings (\$0.17/ft²)
B2 (MPC)	Supervisory MPC, VRF load shifting	MPC vs. baseline across heating and cooling season: 41.2% load shed and 15.2% cost savings
B2 (DFLEXLIBS)	Portable DF rule-based sequences	28.49% cost savings; 7.70 W/m² demand decrease; deployment took less than one day after middleware setup
B3	G36 boiler plant control	7.5% normalized annual gas savings; \$3,662/yr cost reduction (\$0.095/ft²); same sequences deployed as at B1 with no software changes
B4	Supervisory MPC, HP-RTU	MPC vs. baseline across heating and cooling season: 42.1% load shed during high-price period and 30.5% cost savings; 72% reduction in MPC setup time (123 min manual → 34 min semantic)
B5	Supervisory MPC, Multizone UFAD	74% average cost savings over 2-week test with multiday hourly varying prices; semantic queries replaced hundreds of lines of hard-coded conditional logic

At B1, the G36 chiller plant sequences (as s231 FMU) have been running continuously since November 2025. The estimated annual chiller electricity reduction was approximately 15%, corresponding to roughly \$17,334 per year in cost savings (\$0.12/ft²). The hot water reset sequences reduced thermal energy consumption by approximately 12%, with an estimated \$23,860 per year in gas cost reduction (\$0.17/ft²) if a typical boiler is assumed. The semantic model and the CDL FMU contributed directly to efficiency: the same FMU for the chiller was able to be used for the boiler and the SPARQL queries written for the chiller were reused for the boiler by modifying the equipment type to “boiler”, with no other changes to the broader software pipeline.

At the B2, the MPC controller achieved consistent daily cost reductions relative to baseline across both the heating and cooling season, driven by shifting load from high electricity price periods (average 41.2% load shed and 15.2% cost savings). The DFLEXLIBS demand flexibility sequences achieved 28.49% cost savings and a 7.70 W/m² demand decrease. The full deployment, from middleware setup, application configuration and validation to live control, aided by a graphical user interface, was completed in less than one day.

At B3, the G36 boiler control sequences (as s231 FMU) produced a 7.5% normalized annual gas savings and \$3,662 per year in cost reduction (\$0.095/ft²). As the building was already high-performing through efficient condensing boilers and a high-thermal-mass radiant system, any modest reductions in energy consumption are meaningful. Figure 2 presents the hourly average supply water temperature and pump power consumption, along with a box plot illustrating the distribution of values throughout the day. Under G36, the supply water temperature was consistently reset to lower levels during afternoon and nighttime hours. To meet the building’s heating demand under these reduced temperatures, the system compensated with increased hot water flow rates. Despite this rise in flow, the corresponding increase in pump power was minimal and the reduced supply temperature led to a net decrease in thermal energy use.

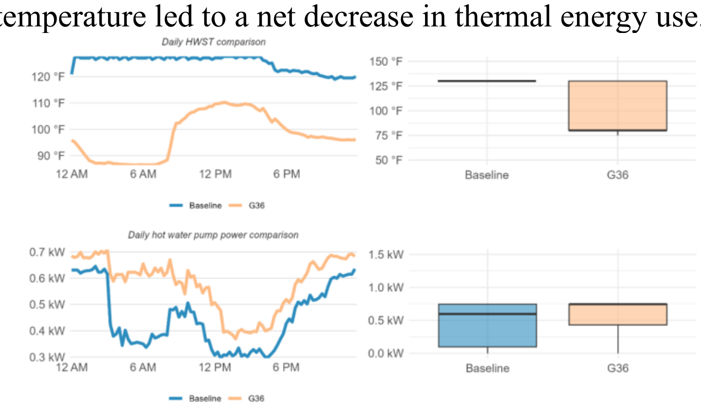

Figure 2. B3 boiler plant control results: Hot water supply temperature and hot water pump power comparison between G36 days and baseline days.

At the B4, the MPC achieved 42.1% load shed during high-price periods and 30.5% cost savings across the heating and cooling seasons. The time taken for configuring the MPC was also tracked with and without semantic modeling. This effort demonstrated a 72% reduction in setup time: the manual process required 123 minutes per zone while the semantic workflow required 34 minutes per zone (Table 3). Table 4 shows the task-by-task breakdown. The largest time savings were in scripting and formatting tasks that semantic model queries automated entirely: zone identification and ID assignment, unit conversion, metadata formatting, and configuration file generation. Site-level tasks requiring explicit physical information collection such as floor area survey and nameplate data collection were unaffected.

Table 4. Breakdown of the time taken to extract building metadata and to configure the MPC controller using a manual approach and a semantic-model driven approach in B4.

Software module	**Metadata Category**	**Metadata retrieval and extraction tasks**	**Details (such as examples of metadata retrieved and processes)**	**Manual (min)**	**Semantic (min)**
System identification (SysID) module	Building metadata	Information survey	- floor area - window area/azimuth	10	10
		Zone identification	Assign unique ID and aggregation	10	0
		Unit conversion	Convert to SI unit	5	0
	HVAC metadata	Information survey	- Nominal capacity - COP - Nominal power	5	5
		Zone identification	Assign unique ID	2	0
		Unit conversion	Convert to SI unit	5	0
	Site metadata	Information survey	- Latitude, Longitude - Timezone	2	2
	Metadata creation	Formatting	Create mapping from building points to the inputs and outputs of SysID module	15	0
	SYSID metadata	Save Metadata	Store data into json	5	0
		Formatting	Create mapping from building points to the inputs and outputs of SysID module	2	2
Model Predictive Control (MPC) module	Building metadata	Information survey	NA	0	0
		zoning	Collect multiple building data	5	0
	HVAC metadata	Information survey	- Setpoint deadband - Thermostat resolution - Thermostat hysteresis	10	10
		zoning	Assign unique ID	2	0
		unit conversion	Convert to SI unit	5	0
	Metadata creation	Formatting/aggregation	Create mapping from building points to the inputs and outputs of MPC module	30	0
		Save metadata	Store the data into json	5	0

	MPC metadata	Formatting	Create mapping from building points to the inputs and outputs of MPC module	5	5
Total				**123**	**34**

At B5, the MPC controller achieved 74% average cost savings over a two-week summer test (7/1–7/11/2025) with highly dynamic electricity prices (hourly changes with different daily profiles repeating weekly) (Zanetti et al. 2026). This substantial reduction was driven primarily by aggressive load shifting, reducing demand by 30-80% during high-price peak periods, enabled by the extreme price arbitrage opportunity created by the dynamic tariff structure. Secondary energy savings resulted from milder weather conditions during the test period and reduced temperature constraint weighting during unattended operation. The semantic model contributed by enabling dynamic discovery of required BAS data points through SPARQL queries rather than manual specification of point addresses, seamlessly handling multiple different zone temperature sensor naming conventions without requiring hard-coded conditional logic, eliminating static property lookups from CSV files by querying building metadata directly from the semantic model, and automatically including remote zone temperature sensors that had not been previously tracked in manual configuration files. Figure 3 shows the normalized hourly energy consumption distribution with MPC on and off, demonstrating that the controller successfully shifts load in response to the price signal.

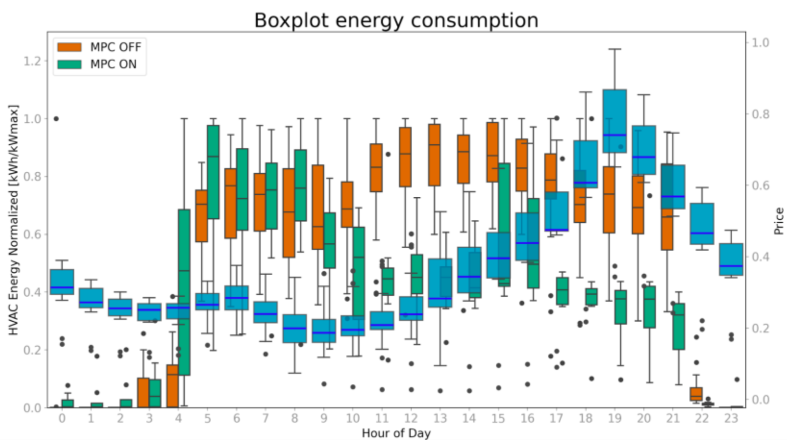

Figure 3. B5 normalized hourly HVAC energy consumption with MPC off (orange) and MPC on (green), overlaid with hourly electricity price signal (blue). The MPC successfully shifts load from high-price afternoon hours toward lower-price periods.

Lessons Learned

- **Semantic model development effort and approach:** Effort ranged from 28 to over 200 person-hours, driven by building size and complexity. Three pathways emerged: (1) refining existing metadata models to s223 specifications (fastest where high-quality metadata existed); (2) building application-specific models (most effective for small buildings); and (3) using templates and semi-automated tools (most efficient where equipment matched available templates). All benefited from interactive SHACL validation, which improved portability by constraining valid representations. At B2, the same semantic model served both MPC and demand flexibility applications without modification.

- **Portability of CDL control sequences:** A significant finding was the ability to deploy CDL sequences across multiple buildings without custom re-programming. G36 CDL sequences developed and validated at B1 (Siemens BAS) were redeployed at B3 (Johnson Controls BAS) without modification, simply by running them against B3's semantic model. This capability is enabled by CDL being supported by ASHRAE rather than a proprietary format. Unlike control logic programmed in vendor-specific languages, CDL sequences can be reused across heterogeneous platforms, avoiding the weeks or months of custom development typically required for control retrofits. This portability depends critically on two conditions: availability of conforming semantic models that provide required data points in prescribed form, and adequate documentation to adapt sequences to building-specific configurations without source code modification.
- **Querying:** All demonstrations successfully queried the information required for their respective applications. However, query portability across differently constructed but equally valid s223 models remained a challenge. Some queries may work for a single building, but when transferred to another building, they may be underspecified. For example, some buildings may have a single point for the HVAC mode, and other buildings may have multiple points to represent the HVAC mode more specifically. A query designed for the first building, expecting a single HVAC mode point may not work on the second. Additionally, for large buildings, semantic inference, a process that applies s223 ontology rules to automatically derive implicit relationships between equipment and data points, inference processes that add new relationships between nodes in the model may take a long time to run. If inference is skipped, however, it can increase query complexity, since the relationships present in the model must be explicitly traversed. This is a significant practical limitation when semantic models get large.
- **Tooling gaps:** Tooling was a consistent concern across all sites. BuildingMOTIF template libraries did not cover all equipment types encountered, particularly heat pumps, radiant systems, and less common air distribution configurations. Validation and inference on large models (exceeding 100,000 triples) was slow with RDFLib/ PySHACL, so migration to Oxigraph/tq-shacl provided meaningful improvement. A result of this exercise was that a graphical equipment modeling interface was identified as a high-priority need. Automated point mapping from BACnet scans to s223 model elements remains an unsolved problem, representing a large fraction of total modeling effort at every site. Some version incompatibilities between legacy software used for MPC and modern semantic libraries were encountered and solving this required an ad-hoc workaround.
- **Value proposition and adoption path:** Where the workflow functioned well, particularly at smaller buildings using application-driven or template-based approaches, the benefits were concrete and measurable: 72% reduction in MPC setup time at B4, sub-day deployment for demand flexibility sequences at B2, and elimination of hundreds of lines of hard-coded logic at B5. At larger buildings, the per-project overhead was harder to justify for a single application, though the reuse of models across multiple applications (controls, dashboarding, commissioning) improved the return significantly. The

demonstrations also highlighted the distinction between per-project benefits and long-term ecosystem value: an interoperable representation enables tool development, interoperability, and cross-building reuse that ad-hoc approaches cannot support.

Discussion and Recommendations

- **For s223 ontology developers:** The hierarchy of enumeration kinds (aspects, roles, property classes) should be reviewed and restructured to improve portability of SPARQL queries. Heat pump and bidirectional flow system modeling should be more thoroughly specified. Model nesting—where a building model is composed of independently valid submodels—should be explicitly supported and documented as a strategy for managing large model performance. Validation error messages should be mapped to human-readable explanations that reference the specific template or constraint that was violated.
- **For tooling developers.** Template libraries should be significantly expanded, with priority given to common packaged equipment types (RTUs, VRF systems, HP-RTUs) and less common configurations. A graphical interface for equipment modeling that encodes allowed relationships would dramatically lower the barrier to entry. Point mapping tools that translate BACnet scans to s223 model elements, even with imperfect accuracy, would reduce the dominant source of modeling effort. Performance optimization for validation and inference on large models is essential for industry adoption; the migration from RDFLib/PySHACL to Oxigraph/tq-shacl demonstrated that meaningful improvement is achievable within the open-source ecosystem.
- **For practitioners and building owners.** Application-driven modeling with integrated SHACL validation is recommended as the most effective workflow for small to medium-sized buildings undertaking a first implementation. The survey-based workflow is recommended when building equipment matches available templates. Regardless of approach, early definition of the SPARQL queries and validation shapes required by the target application focuses modeling effort and prevents over-specification. Plan for a significant learning investment on the first project; expect subsequent projects in the same building class to be substantially faster. The reuse of sequences and queries across buildings, as demonstrated at B1 and B3, should be explicitly planned for from the start, as it is one of the strongest economic arguments for semantic modeling investment.
- **For researchers.** LLM-assisted modeling is a promising direction but requires template-constrained prompting to reduce hallucination of invalid class names (Paul et al 2025a). Model nesting and hierarchical inference warrant investigation as strategies for large building performance. Cross-building query portability, and the tradeoffs between prescriptive and permissive modeling, merit a systematic study. The demonstrated potential of a single semantic model serving multiple applications simultaneously (controls, demand flexibility, dashboarding, commissioning) should be quantified more rigorously across a larger building portfolio.

Conclusion

This paper reports on field demonstrations of two complementary ASHRAE efforts: s223 (semantic data models) and s231 (Control Description Language). Applied across five California buildings, they enabled diverse control applications from G36 supervisory control to model predictive control and demand flexibility sequences. Results show that s223 can represent information required by diverse applications and s231 CDL sequences can be authored, validated, and deployed using interoperable tools without vendor lock-in. Together they delivered measurable benefits: 72% reduction in MPC setup time, sub-day demand flexibility deployment, and elimination of hard-coded logic. The ability to reuse both CDL sequences and semantic models across different BAS platforms without modification demonstrates that interoperability delivers concrete economic value by replacing weeks of custom development. However, significant challenges persist. Learning both s223 and s231 requires substantial expertise. Tooling has gaps in template coverage and performance. Large semantic models cannot yet be validated efficiently with open-source tools. Query portability and broader CDL adoption beyond research remain open problems. Addressing these challenges requires coordinated effort across ASHRAE technical committees, tooling developers, and the building controls community. These demonstrations establish a baseline for measuring progress as adoption of s223 and s231 grows.

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