Building Technologies & Urban Systems Division
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Digital and Interoperable: The future of building automation is on the horizon. What's in it for me?

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ABSTRACT

Control and analytics retrofits in commercial buildings provide owners and operators with tools for improved maintenance and operations, and are an effective strategy for advancing the ambitious carbon reduction objectives mandated by state and federal governments. However, current retrofit processes are labor-intensive, error-prone, and expensive, thereby limiting scalability. There are two primary issues. First, control sequences are: a) typically manually specified in English language using non-standard terminology; b) often not tested prior to installation; and c) more complex when they aim for higher performance (greater efficiency, grid-flexibility). Second, naming conventions used to label the data are often inconsistent, and may vary by practitioner and project. These problems result in significant manual labor and increased cost, lead to malfunctioning operation, and limit scaled deployment of new, high performance control sequences such as needed for heat pump plants with energy storage.

This paper presents recent progress towards digitization of these processes, facilitated by two new ASHRAE standards that underwent first public review in 2024. Standard 231P facilitates vendor-neutral, machine-readable representations of control sequences, enabling creation of vendor-agnostic libraries of high performance control sequences that can be translated digitally to building automation systems. Standard 223P facilitates interoperability between controls/analytics and building systems by enabling semi-automatic configuration using semantic models.

We first provide a preliminary glimpse into the content of these new standards. Second, we describe their relationships with the established ASHRAE Standard 135 (BACnet communication protocol) and Guideline 36 (high-performance control sequences), and suggest how new automated techniques can be integrated with current human-centric practices. Finally, we discuss how the proposed workflows could impact different industry stakeholders, including owners, designers, control vendors, installers, commissioning agents, and facilities managers.

These standards and guidelines enable new workflows that can significantly reduce deployment efforts and costs, and provide a path for scaled deployment of new sequences such as needed for combined chiller and heat pump plants.

Introduction and Motivation

The United States is striving towards ambitious climate mitigation objectives, aiming to reduce greenhouse gas emissions from U.S. buildings 65% by 2035 and 90% by 2050 compared to 2005, while centering equity and benefits to communities (Langevin et al. 2024). Controls play a crucial role in ensuring buildings reach their full potential in increasing building efficiency, accelerating on-site emissions reductions and transforming the grid edge. Commercial buildings account for 34% of energy-related emissions nationally, and large commercial buildings represent over half of total commercial sector energy use and floor area (EIA 2018). Recent research for these buildings indicates a 29% energy waste (and associated emissions) is attributable to controls, along with a potential for peak load reduction of 19% (Fernandez et al. 2017). A field survey showed that in large commercial buildings with built-up HVAC systems, programming errors are the leading cause of control related problems (Barwig et al., 2002) Further, other studies demonstrate that manual commissioning can lead to a 6% energy savings, while Automated Fault Detection and Diagnostics (AFDD) can achieve a 9% reduction with a payback period of two years (Crow et al. 2020; Kramer at al. 2020).

Challenges in realizing these potential benefits stem from the complexity and heterogeneity of building control systems, as well as current practices and workflows to implement any control commissioning or control upgrade. We describe a few of them below.

1 - Large Commercial Buildings are Complex and Heterogeneous

Large commercial buildings are complex and heterogeneous with diverse loads, end-uses, and services (Seyam 2018). Controls are implemented on building-by-building basis and any commissioning or control retrofit activity has to be customized to the specific site, and treated as a separate project, often involving software and data integration (Granderson et al. 2011). This practically limits the scalability of the retrofits.

2 - Conventional Control Sequences are Inadequate while Modern Ones are Too Complex

Conventional static rule-based control sequences of operations (SOO) are devised to uphold temperature and humidity conditions, rather than prioritizing optimization for energy, emissions, health, and load management. These SOO are neither sufficient to guarantee efficient operation, nor enable grid flexibility. More complex SOO, such as the ones described in ASHRAE Guideline 36 require 6 to 7 times more lines of code compared to the traditional ones (Wetter et al 2022). This is supported by advances in building management system technology. Further, best-in-class SOO for demand flexibility applications have not been codified in standards or guidelines (Granderson et al. 2024). SOO for combined chiller and heat pump plants are even more complex, and have been shown to be problematic to deploy robustly (Vetterli and Sulzer 2015, and Fumagalli et al. 2017)

3 - The Current Control Delivery Process has not been Designed for High Performance Control Sequences

Today's control delivery process, which involves designing and implementing control strategies, relies on manual methods. It entails interpreting English-written documents and translating them into code by control contractors on a project-by-project basis (Wetter et al. 2022; Paliaga et al. 2020). Figure 1 illustrates the entire process for controls retrofit, along with the entities involved. Initially, a building owner or operator creates a request for proposal (RFP) or requirement document. Subsequently, control designers generate a design intent document and formulate the SOO in English. Frequently, these SOO are derived from previous specifications or are adapted from prior projects to reduce the time needed to write them. Following this, control contractors, typically separate entities from control designers, receive the document and are tasked with deciphering the language to produce a control program. This program is then uploaded into a control system and deployed in the field so that it can be tested (e.g. by a commissioning agent) and then put into operation. Currently, there is only research code available to validate the SOO before implementation in the actual building. With increasing complexity in the SOO, errors and suboptimal performance are frequently encountered. Certain adjustments to the control code are made by technicians onsite to troubleshoot the code, tune control parameters, and customize the program if the real conditions in the field differ from the expected ones. Required modifications of the SOO are also difficult to implement since the code is highly customized and often not well documented. Overall, this workflow is characterized by its time-consuming nature, susceptibility to errors, heightened risk, and often fails to yield high-performance SOO (Wetter et al., 2022).

Moreover, the effectiveness of suggested control retrofits are seldom tested but rather based on the preferences and experience of the mechanical designer. For performance-based, cost-effective, robust design and operation, more fluidity between data models, energy models, and control delivery and verification processes are needed as argued in Wetter et al. (2023), for which standards presented here are one necessary contribution.

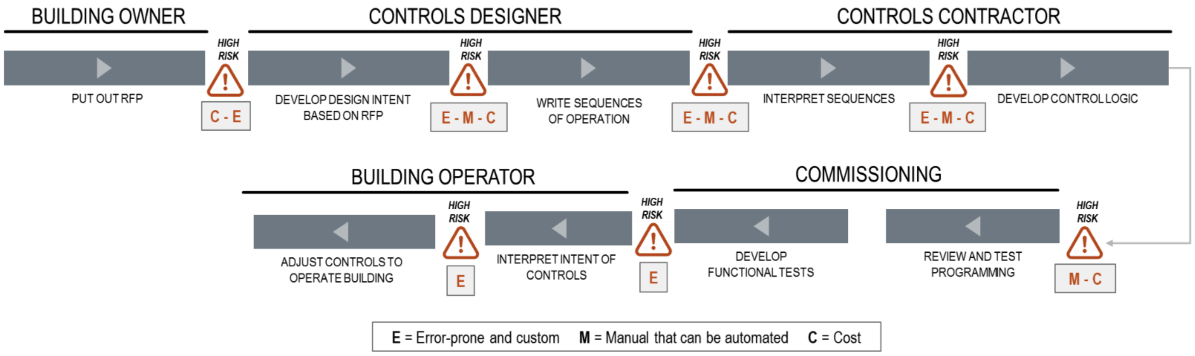

Figure 1: Conventional control delivery workflow (Paliaga et al., 2020)

4 - Controls and Analytics Applications are Siloed and not Interoperable

During the lifecycle of the building other control or analytic applications may be added to the building. As an example, fault detection and diagnostics (FDD) tools belong to the category of energy management and information systems (EMIS) (LBNL 2015). They offer a method of monitoring-based commissioning, allowing for the ongoing identification, isolation, and resolution of operational inefficiencies by operations and maintenance personnel (Lin et al., 2020). As with other EMIS technologies, these tools must integrate with building automation systems (BAS) but their installation and configuration are often labor-intensive and time-consuming. Apart from the necessary effort to establish a cyber secure connection between the FDD tool and the BAS, configuring the FDD rule demands substantial understanding of the building and its systems, including the type of sensors, physical location, system capabilities, schedules, and SOO (Pritoni et al. 2021). Since this "metadata" is often missing in the BAS, the engineers need to map them to a consistent and expressive (semantic) data model (Bergmann et al., 2020). This undertaking demands considerable effort and, if relying on bespoke semantic schemas, must be carried out anew whenever a new application is introduced to the ecosystem. Although many contemporary EMIS products employ internal semantic schemas, these models lack standardization and are frequently not shared with other vendors. As a result, integrating a new application from a different vendor into the building requires an additional bespoke integration, rendering the process non-scalable.

In the last decade, several initiatives have emerged to solve this problem. Among them are Project Haystack[1] and the Brick Schema[2], both serving as open schemas enabling a common structure and vocabulary for semantic metadata of buildings. These frameworks can facilitate the sharing of common models among application providers (Pritoni et al. 2021), but have not undergone standardization through a formal process. Moreover, they have not been designed to represent the detailed topology of equipment and building systems, which may be required for high-performance controls and analytics algorithms. This often resulted in the proliferation of customized implementations, hampering interoperability. Further, they are in need of a more formalized validation, improved documentation, examples, tooling, and workforce education to enable widespread adoption (Bergmann 2020).

5 - Workforce Capacity and Skills are Inadequate

The current workforce is declining in size and it is ill prepared to implement complex controls and commissioning the new generation of smart buildings (Truitt et al. 2022).

This paper describes a set of ASHRAE standards and guidelines that aim to address these challenges. We then present examples of how the standards can support digitization and automation of common processes. Finally we describe how these new workflows will impact different stakeholders in industry and governments.

Complimentary ASHRAE Standards and Guidelines

For several decades ASHRAE has been at the forefront of developing standards and guidelines to improve operational efficiency, air quality, and occupant comfort in buildings. Figure 2a depicts a guideline and three standards, two of which are currently under review, that are synergistic with each other and can help address the challenges outlined above.

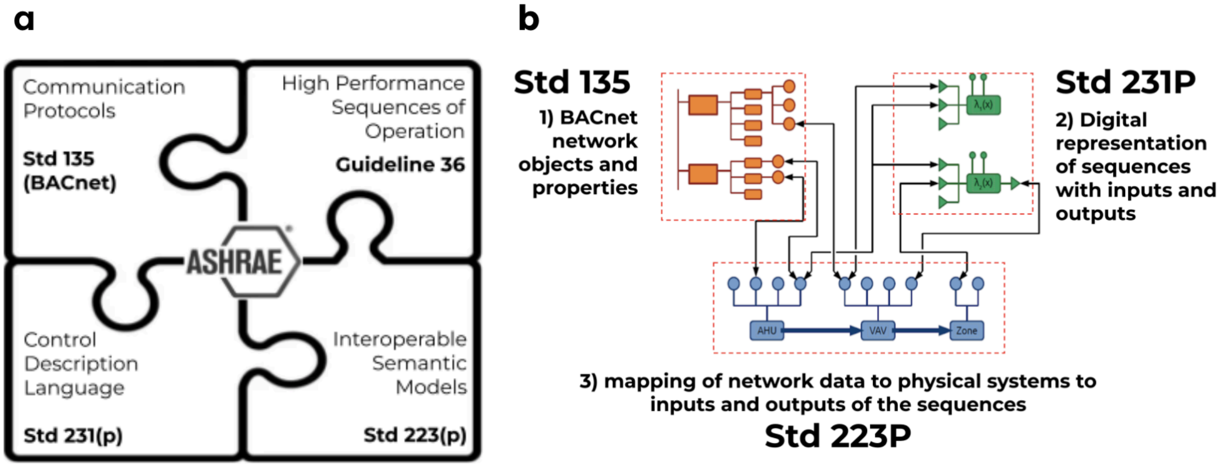

Figure 2: (a) Synergistic ASHRAE standards and guidelines that facilitate digitization of controls and analytics (b) the integration of concepts across the synergistic standards

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[1] https://project-haystack.org/

[2] https://brickschema.org/

The three standards are complementary in that they each address different aspects of control delivery. Standard 135 defines how devices and systems communicate, while standard 231P specifies the control logic that uses the current state of the system to calculate new setpoints and actuation signals. Standard 223P defines building equipment and describes the topology of building systems, such as the connection between HVAC equipment and thermal zones. This complementary approach, known as orthogonalization of concerns, allows for focused definition of individual standards that, when combined, enable comprehensive system-level workflows.

Standard 135 (BACnet)

The ANSI/ASHRAE BACnet Standard 135, first published in 1995 and most recently updated in 2024, had an important role in allowing proprietary control systems to communicate with each other. Before its introduction, the building automation market was very fragmented and each technical solution used proprietary communication protocols that did not allow intra-platform communication (Goldschmidt 1998). Now the protocol is widely used, with 77% global market share and higher penetration in North America[3]. BACnet defines data communication services and protocols for monitoring and controlling Heating, Ventilating, Air Conditioning, and Refrigeration (HVAC&R) and other building systems. It also defines an abstract, object-oriented representation of information communicated between such equipment, thereby facilitating the application and use of digital control technology in buildings. This protocol models each building automation device as a collection of data structures called 'objects,' the properties of which represent various aspects of the hardware, software, and operation of the device. These objects provide a means of identifying and accessing information without requiring knowledge of the details of the device's internal design or configuration (ASHRAE 2023). The protocol enables what is often called “technical” interoperability between systems (Pritoni et al., 2021), that is, the ability for a device to connect in a network with other devices and exchange messages that can be syntactically understood. BACnet Secure Connect (BACnet /SC) augments the BACnet protocol by providing a secure and encrypted data link layer that allows two BACnet devices to communicate over this encrypted connection (Fisher, 2020).

Adoption and availability to industry: although legacy control systems may continue to rely on proprietary communication protocols, BACnet is extensively adopted within the industry, with most vendors incorporating support for it in their new products.

Testing: the BACnet Testing Laboratories was developed as an internationally recognized testing and listing program to ensure products comply with the standard[4].

Tools: a multitude of open-source tools[5] have been developed for BACnet throughout the years, increasing adoption and creating an ecosystem.

Aspects not addressed: as BACnet is a standard for communication, it does not provide a means to express the control logic of the system. This is where Guideline 36 came into play, describing how HVAC systems should be operated.

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[3] according to BACnet International. https://bacnetinternational.org/news/bacnet-protocol-expands-dominant-market-share-in-latest-market-research-report/

[4] https://btl.org/btl-certification-program/

[5] https://bacnet.sourceforge.net/

Guideline 36

In 2008, ASHRAE started a research project to develop comprehensive optimized SOO for common air distribution and terminal subsystems (Hydeman et al. 2014). At the end of the project, ASHRAE formed a committee to publish and maintain these SOO and future SOO for other systems (Paliaga et al. 2020). This led to the publication of these SOO in Guideline 36-2018 – High-Performance Sequences of Operation for HVAC Systems (ASHRAE 2018), also summarized in (Taylor 2018). “ASHRAE Guideline 36 provides uniform SOO for HVAC systems that are intended to maximize the systems' energy efficiency and performance, provide control stability, and allow for real-time fault detection and diagnostics. Standardized advanced SOO provides benefits including reduced engineering time, reduced programming and commissioning time, reduced energy consumption, improved indoor air quality, and a common set of terms to facilitate communication between specifiers, contractors, and operators” (ASHRAE 2023). While the 2018 version was for air-side systems, the 2021 version of the guideline added SOO for boilers and chilled water plants (ASHRAE 2021).

Adoption and availability to industry: while these SOO represent a significant improvement over the status quo, demonstrating up to a 30% reduction in energy use (Zhang et al. 2022) their adoption has been slow (Faulkner et al. 2023). There are several obstacles, including but not limited to the challenges mentioned in the previous section, hindering their broader acceptance. The process relies on English-language descriptions of the SOO, presented in a lengthy document exceeding 300 pages. The SOO are typically published before extensive closed loop testing of all combinations of system types that should be supported. The SOOs need to be reprogrammed and/or edited to adapt to the specific system configuration at hand which further introduces risk of errors. Further there is no clear mechanism or tool for validation of the code generated before installation in the field.

Aspects not addressed: lack of a digital representation of these SOO gave rise to the development of the Control Description Language which was first published in Wetter et al. (2018) and served in 2020 as an input to the formation of the proposed ASHRAE Standard 231P Committee.

Standard 231P[6]

In 2020 ASHRAE established a committee to standardize a computer language to express control sequences. The standard defines “a declarative graphical programming language for building SOO that is both human and machine readable, designed for specification, implementation through machine-to-machine translation, documentation, and simulation” (ASHRAE 2023). Standard 231P standardizes the Control Description Language (CDL) for developing these SOO (Wetter et al., 2018). CDL is a subset of Modelica Language and hence, Modelica[7]-based simulation tools can be leveraged to support development of control sequences and libraries of customizable SOO, and to do simulation and formal verification (Wetter et al., 2022). The standard also formalizes the Control eXchange Format (CXF), which is a linked-data representation of the CDL SOO serialized in JSON-LD[8], meant for SOO exchange and translation. The standard is focused on HVAC use cases, but is applicable to other building control domains including lighting and domestic hot water.

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[6] "P" indicates that the standard is proposed and has not yet been approved at the time of writing.

[7] https://modelica.org/

[8] https://json-ld.org/

Status: at the time of writing this article, this standard has completed its first public review.
Tools: there is an associated project conducted by the US Department of Energy's National Laboratories that has been developing tools in support of the proposed standard, and that implemented SOO libraries and tutorials based on this proposed standard. The Modelica Buildings Library (Wetter et al. 2014) contains a reference implementation of CDL that has been used to construct customizable libraries of HVAC SOO. The library contains CDL implementations of Guideline 36 and a variety of other SOO, along with open and closed loop tests for each sub sequence. These SOO libraries, together with associated HVAC templates, are used in ctrl-flow[9], a web-based tool to customize SOO specifications to a particular building. A new project funded by the Department of Defense will extend ctrl-flow to incorporate more SOO and export CDL and CXF versions of the SOO, along with the English language specification and other documents, such as point lists and semantic models. ctrl-flow, and the exported document, relies on modelica-json (Wetter et al. 2021), a software that translates CDL SOO into their CXF equivalents. modelica-json also supports the extraction of embedded semantic metadata from Modelica models. Constrain (Chen et al. 2023) is a related tool in the DOE portfolio that leverages data-based techniques to verify whether the building systems are operating as intended.
Aspects not addressed: note that while the standard supports the inclusion of semantic information about the inputs and outputs, its purpose is not to define a semantic model, as this is the scope of standard 223P.

Standard 223P[6]

In response to the need for consistent representations of building semantic metadata, the ASHRAE BACnet committee created a Semantic Interoperability Working Group, with the goal to harmonize and extend existing semantic schemas and provide machine-readable and standardized semantic descriptions of data relevant to building automation (ASHRAE, 2018). Arising from earlier attempts to establish descriptive "tags" for organizing building data, the standard scope has evolved to offer comprehensive semantic metadata, making use of semantic web technologies (Peinl 2016). “The purpose of this standard is to define formal knowledge concepts and a methodology to apply them to create interoperable, machine-readable semantic frameworks for representing building automation and control data, and other building system information (ASHRAE 2023). This proposed standard provides a comprehensive way to apply semantic formalisms to represent the context of building system data and relationships between the associated building system components so that software applications can find and understand the information in an automated way. It is intended to facilitate the development and implementation of building analytics tools and enterprise knowledge applications that can implement many building system functions, including: 1) automated fault detection and diagnostics, 2) building system commissioning, 3) digital twins, 4) real-time optimization 4) smart grid interactions.[10] The standard provides constructs for modeling system types across building domains, including lighting systems, domestic hot water, electrical networks and more. This can enable data visibility across traditionally siloed systems within a building. The goal of the standard is to enable automatic configuration and installation of control and analytics software, enabling “plug-and-play” behavior, similar to what we expect from mobile applications (Roth et al. 2022).

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[9] ctrl-flow.lbl.gov

[10] https://docs.open223.info/explanation/purpose_scope.html

Current modeling constructs in 223P allow for mapping BACnet devices, objects, and properties to the actual equipment and systems in buildings, and mapping of the data points of these entities to the inputs and outputs of control logic of the SOO, defined by 231P, as depicted in Figure 2b. This framework ensures seamless traceability from an input for a control logic to the related device and its BACnet identifier.

Status: At the time of writing, the standard has completed advisory public review, and is preparing for formal public review and publication later in 2024 or 2025.

Tools: There are currently two tools to support and enable adoption and use of the proposed Standard. The Open223 sites include example models of real and fictitious buildings, ontology-explorers to view the ontology, query tools to investigate the standard and models, and a user guide that provides explanations, tutorials, and guides on standard usage[11]. The BuildingMOTIF toolset, under development at the time of writing, will automate the creation and validation of semantic models and allow interoperability between metadata schemas (i.e. Haystack, Brick, and 223P)[12].

Digitization and Automation of Common Processes

Practices for control retrofits vary based on organization and building type across the country, reflecting the diverse needs of different sectors and regions as well as local codes and regulations. Drawing from extensive industry conversations and interviews, we showcase three examples of common retrofit processes to demonstrate how the new ASHRAE standards and guidelines facilitate the digitization of controls and analytics, enabling new workflows that improve their delivery while reducing costs. These are: 1) controls retrofit process 2) FDD deployment, and 3) functional testing for commissioning controls. These are not meant to be exhaustive, but just illustrative.

Controls *"design-bid-build"* Retrofit

The traditional controls "design-bid-build" retrofit process common in many regions of the United States heavily relies on the exchange of English language documents and the use of disconnected tools that need manual data input (Kubba, 2017). The process is error-prone and can cause loss of information and increase in costs. The new standards can improve this workflow benefiting all stakeholders involved (Figure 3).

In today's process, the first step is for the general contractor and design engineer to create an RFP based on the building owner's interests. As a control retrofit is often part of a larger mechanical retrofit, this RFP can include SOO and specifications for mechanical, electrical, and plumbing systems. Contractors then develop designs and cost estimates based on the relevant sections within the RFP. During this process, conflicting or vague information is often identified in the RFP document, leading to iterative communication between bidders and mechanical designers through Requests for Information (RFIs), ultimately resulting in refinements to the RFP. The RFP is not provided in machine-readable format to the contractors, creating the opportunity for erroneous bids. At the end of the process, each control contractor submits their bid containing cost estimates for hardware, labor and a description of the SOO. After the bid is accepted, the contractors develop submittals, finalizing what will be installed. Often, the tools and people developing the final design, including drawings and specifications, differ from those

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[11] https://open223.info/

[12] https://buildingmotif.readthedocs.io/

in the bidding process, requiring the manual re-entry of information. Additionally, when the control system is installed, the actual programs do not typically use the digital information generated by the previously used tools.

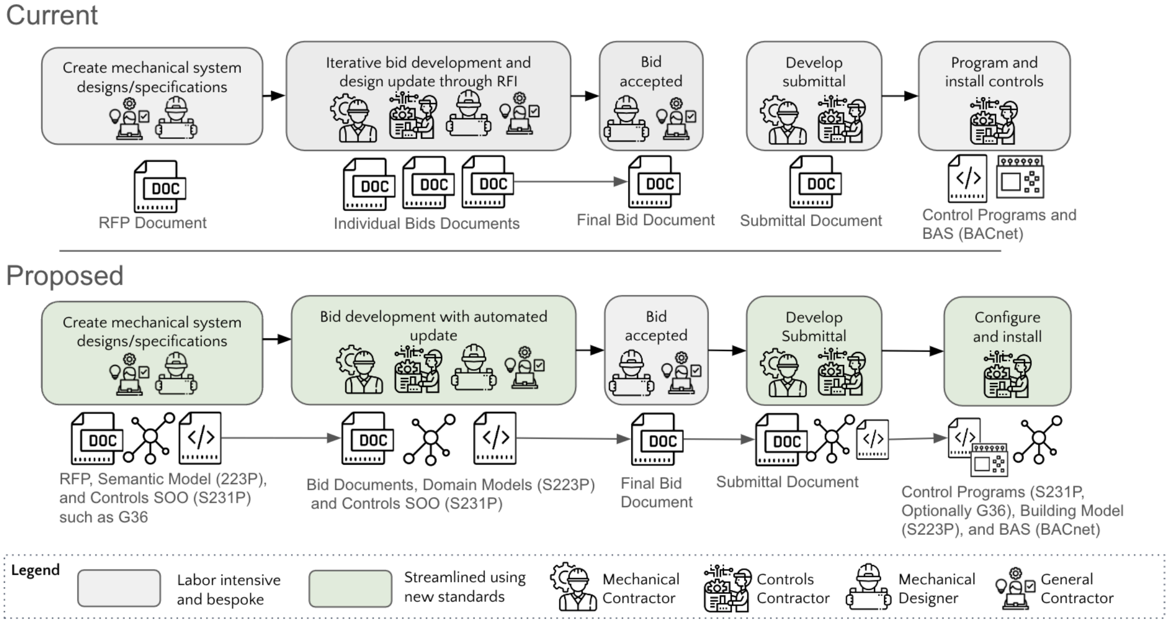

Figure 3. Controls Retrofit Bidding Process

The new standards enable building tools and creating new, digitized workflows that can reduce errors and costs for all stakeholders, while delivering greater value to building owners with high-performance controls and interoperable data models that support subsequent applications. Through digitization, high performance SOO can rapidly be scaled to industry. These include new SOO for grid-responsive, combined chiller and heat pump plants with storage with which the industry has little experience. Utilizing new tools such as ctrl-flow, mechanical design engineers can select from a list of high performance SOO, described in a vendor-neutral format defined by Standard 231P. These SOO have been extensively tested in simulation with an energy model in the loop prior to deploying them to industry through the ctrl-flow software. Optionally, the digital representation of the sequence can also be used on a per project basis to further optimize them through energy modeling (Gautier et al., 2023). A semantic model, using Standard 223P, can also be linked to the inputs and outputs of the SOO. Cross-domain semantic models can provide understanding of building system designs across contractors, reducing costly procedures to update designs and correct errors. These digital SOOs and semantic models can be directly specified in the RFP. During the bidding process, the bidding tool can ingest and use this digital information, reducing the opportunity for error in interpretation. If updates to the RFP are necessary, they can be communicated to all contractors in a consistent and clear manner. Once the bid is accepted, the digital SOO and semantic model can be transferred from the bidding stage to the detailed design stage and used to create the final submittal. The control logic can be translated from 231P to the building automation system. One of the greatest benefits of this approach is in carrying the information generated during the bidding process through the controls deployment. Additionally, the 231P controls description and 223P building model can be used to automate the configuration of graphics, alarms and BACnet networks, vastly reducing deployment burdens.

FDD Deployment

FDD tools are often deployed after the installation and configuration of the BAS, sometimes years later, and typically have to manually gather and interpret the information related to SOO and equipment configuration used during the BAS deployment. The application of the new standards can significantly reduce their implementation cost and facilitate broader adoption. Figure 4 depicts the traditional and new suggested workflow.

The traditional deployment process for FDD tools in buildings involves various labor-intensive tasks, especially when the provider of the tool is different from the BAS vendor. Following installation and integration with BAS data, configuring FDD rules requires consideration of equipment characteristics, implemented SOO, and an understanding of BAS data points. Manual collection and interpretation are typically required due to the often missing semantic information needed to describe these aspects (Lin et al., 2022). Building system information is gathered from scattered documents such as floor plans and as-built diagrams, as well as text labels describing BAS data. This information describes the topology and characteristics of building systems and controls programming details. There may be information missing, inconsistent, or incorrect requiring significant effort by the FDD provider and facility manager to understand it. Furthermore, certain FDD rules require an understanding of the underlying SOO, which can be obtained through: a) examining the control code, typically customized for a specific building and not easily interpretable; b) reviewing available English documentation of the SOO, which may not be current with the implemented SOO; or c) interviewing control contractors or facility managers, who may not recall the specifics implemented in the control system. The gathered information is then mapped to an internal data model unique to each FDD provider. This semantic data is then used to configure FDD rules and dashboards. The manual nature of these tasks not only increases the likelihood of errors but also makes the process time-consuming and costly.

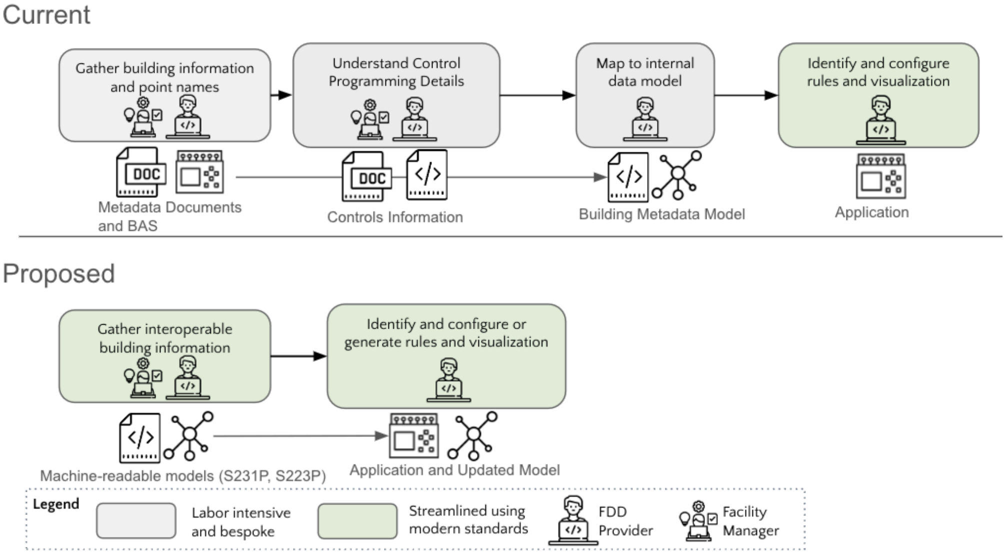

Figure 4: FDD Deployment Process

The introduction of ASHRAE standards 223P and 231P can significantly streamline the FDD deployment process. If semantic information already exists, 223P and 231P models should contain all the details necessary for configuration of FDD rules. The availability of digital control descriptions through 231P enables additional FDD capabilities that require in-depth understanding of the control programming. For example, certain modes, such as morning warm-up, night flushing, and standby, are not always included in the control logic of an HVAC system. A digital representation of the SOO would allow for the automatic or semi-automatic association of the correct FDD rule applicable to such HVAC systems. If 223P and 231P models are not available, this information can be generated during the configuration of the FDD tool utilizing tools such as BuildingMOTIF (Fierro et al., 2022). BuildingMOTIF drives the semantic modeling process based on the data needs of specific applications, streamlining the process of model creation and ensuring that the semantic model is constructed correctly. The resulting semantic models can be used in the future to facilitate simpler configuration for new applications implemented afterwards, such as supervisory control or integration with work-order systems.

Functional Testing for Commissioning Controls

When controls are upgraded, the newly developed and deployed control programs must be tested to ensure that all components, equipment, systems, and system-to-system interfaces are installed as specified and operate according to the requirements. These tests aim to verify the correctness of the control logic relative to the design specifications, ensure the proper operation of the HVAC equipment and components (e.g., identifying failed sensors), and confirm that the system meets building-level performance metrics. The tests are often mandated by energy codes or required by the building owners.[13] The functional tests are frequently developed and performed by a third party commissioning agent. This involves creating test procedures and documents based on the SOO, point lists and mechanical drawings. Typically, the testing procedures are not created using the digital information about the SOO or semantic representation of the buildings and when performed (e.g., opening and closing dampers), they are executed manually via the BAS interface. Additionally, any operational errors identified during commissioning are corrected by the controls contractor via manual edits to the control code. These changes are typically not integrated back into the control library, resulting in the same issues being repeatedly addressed. Furthermore, the drawings and documentation of the deployed sequence are often not updated, leading to discrepancies between the design and the as-built control program. The new standards provide an opportunity to digitize these processes, enhancing their cost-effectiveness.

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[13] https://energycodeace.com/site/custom/public/reference-ace-2016/index.html#!Documents/127functionalperformancetesting.htm

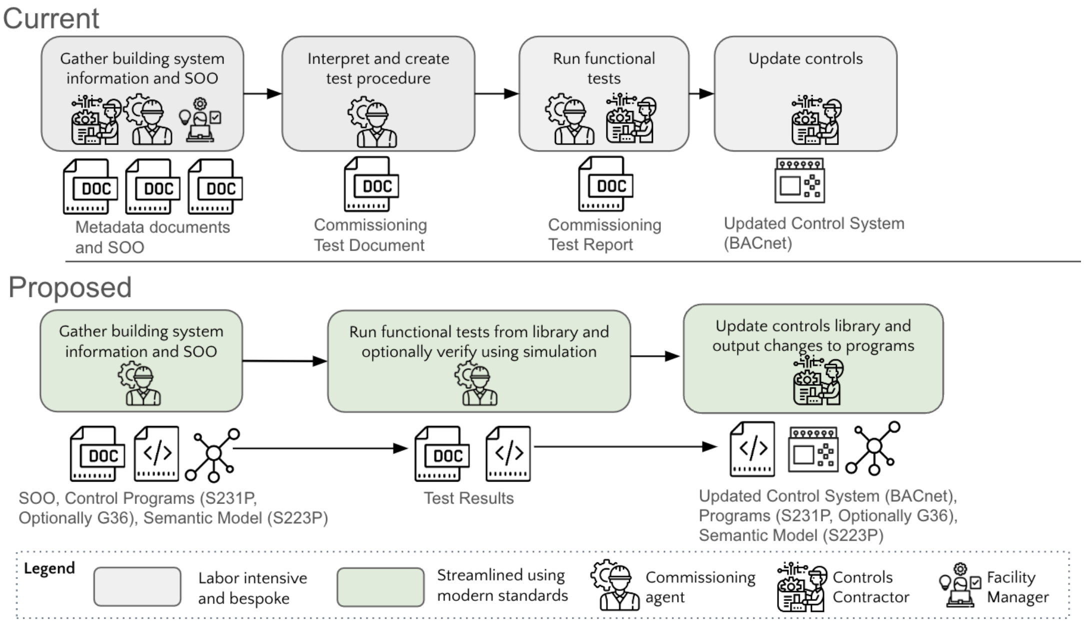

Figure 5. Functional Testing to Commission Controls Process

The proposed workflow, facilitated by ASHRAE standards 223P, 231P, and Guideline 36, transforms this process into a more streamlined and automated series of steps (Figure 5). In this improved workflow, the creation of these testing procedures can be integrated with the rest of the control delivery process. As described in the first example, the mechanical designer begins by identifying and selecting standardized SOOs and control programs from established guidelines such as ASHRAE Guideline 36, which are shared using 231P. Alternatively, if a 223P model already exists for the building, it is possible to identify a subset of applicable SOOs by matching the inputs and outputs from the sequences in the SOO library with the entities available in the model. The use of standardized SOO ensures consistency and scalability of best practice across the industry and significantly reduces the time required for sequence development and testing. A functional test procedure could be generated for each one of these standardized SOO in the library, exemplified by existing tools like HVAC-Cx[14], and linked to the actual system via the semantic model. The digital nature of the sequence also enables commissioning agents to validate the correctness of the SOO implementation based on specifications by connecting it to a dynamic model of the HVAC system and the building (Wetter et al. 2022). After control installation, the actual test to verify that all the components respond as expected, can also be performed in a highly automated way by leveraging the connection between the digital representation of the test procedure and its corresponding points in the BAS, represented in the semantic model. Automation in the test can be achieved through the BAS or the EMIS tool, for example, by overriding commands using references to BACnet objects and properties contained within the semantic model (Pritoni et al., 2022). When updates to the control code are needed to accommodate various system configurations or edge cases, they can be fed back into the controls library, eliminating the need for reprogramming in the future. This digitized process can reduce errors and labor, thereby increasing cost effectiveness and control performance.

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[14] https://www.nist.gov/services-resources/software/hvac-cx-building-hvac-systems-commissioning-tool

Stakeholder Benefits (What's in it for me?)

The three examples described above introduce workflow improvements facilitated by the emerging standards and guidelines. These improvements provide benefits to several stakeholders. We consider five categories of stakeholders: 1) building owners and managers, 2) designers and contractors and implementing controls and analytics, 3) vendors of control systems and equipment, 4) utilities and energy providers, and 5) governmental bodies. Table 1 summarizes our findings from interviews and informal discussions about the new workflows presented above with these stakeholders. Overall, most stakeholders recognize the value of the new standards and tools, appreciating benefits like cost reduction, reduced risk, and improved system performance leading to enhanced customer satisfaction. However, several open questions need to be addressed, including concerns about market demand, technical challenges, and new workforce requirements.

Table 1. Stakeholder benefits and open questions of the new workflow enabled by ASHRAE Standards and Guidelines

Stakeholder	Expected Benefits	Open Questions and Doubts
Building Owners and Managers	● Reduced capital cost for controls upgrades ● More consistent quality and reduced risk for control upgrades ● Greater value for the property ● Reduced vendor lock-in ● Improved efficiency and reduced operational cost ● Easier path to code compliance for retrofits ● Reduced delivery time of control upgrades	● Who is going to maintain and update semantic models and SOO in case of building/controls upgrades? ● How can we validate compliance with these standards for each bid? ● Can the standards be integrated with my existing BAS? ● Is there going to be a cost-premium for products that adopt these new standards?
Designers and contractors implementing controls and analytics[15]	● Improved customer satisfaction ● Availability of a well-tested repository of configurable SOO. ● Reduced transaction cost during bids ● More streamlined retrofit process ● Easier coordination with other contractors ● Reduced risk due to incorrect interpretation of the requirements ● Reduced time and cost to integrate with other software ● Larger total market potential	● How can these new tools accommodate the customization necessary for each building? ● Is there going to be enough market appetite to motivate investments in developing new products and tools that support these standards? ● When are commercial tools that use these standards going to be available to industry? ● How much are the new tools going to cost? ● What types of workforce skills will these new tools require? ● If contracts are awarded solely based on the lowest cost bids, will this cause me to lose opportunities?
Vendors of control hardware and equipment	● Opportunity to sell new value-added services ● Reduced retrofit project costs grow	● Is there a strong enough business case for hardware manufacturers to adopt these standards?

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[15] This category includes: general contractors, mechanical contractors, controls contractors, FDD providers, commissioning agents

	market for new equipment	
Utilities and energy providers	- Improved energy efficiency and demand flexibility in buildings - Improved adoption for complex electrified equipment (e.g. heat pumps plants)	- Can utilities or aggregators leverage standards for scalable demand flexibility? - Can utilities make use of emissions reduction opportunities in buildings?
Governmental bodies	- Ability to scalably achieve carbon-reduction targets for buildings	- What policies can incentivize the deployment of these standards and improved building performance?

Conclusion and Future Work

Control and analytics retrofits provide building owners with essential tools for enhanced maintenance and operations, providing higher performance and energy cost reduction while aligning with ambitious carbon reduction goals set by state and federal governments. However, current retrofit processes are labor-intensive, error-prone, and costly, limiting their scalability and effectiveness. They also do not support scaling best practices in controls, a problem that we expect will become more pronounced as the industry needs to rapidly move towards heat pumps systems with storage for which it lacks the experience and the technical expertise, a problem that was encountered in other countries.

This paper highlights recent advancements toward addressing these major challenges through digitization, facilitated by the introduction of new ASHRAE standards, 231P and 223P. Standard 231P offers vendor-neutral, machine-readable representations of SOO, enabling interchange and closed-loop testing prior to and after installation. Standard 223P enhances interoperability between controls, analytics, and building systems by supporting semi-automatic configuration through semantic models and information sharing between various stakeholders. These standards, working in conjunction with other ASHRAE standards and guidelines, pave the way for new workflows that can substantially reduce efforts and costs associated with design, configuration, and commissioning. We present three examples of proposed workflows enabled by the new standards: controls “design-bid-build” retrofit, FDD deployment and functional testing.

By reducing manual labor, improving accuracy, and enhancing interoperability, these standards will significantly benefit industry stakeholders, including building owners, designers, control vendors, installers, commissioning agents, and facilities managers, as well as utilities and federal and state governments who set forth ambitious decarbonization targets. Future work should address the open questions expressed by stakeholders about the application of these standards, by accelerating their development, demonstrating their benefits, developing workforce training, providing scalable tools for robust project delivery, and fostering industry collaboration. The standards provide individual benefits to each stakeholder during a retrofit process, but provide far greater benefits to the industry as a whole when broadly adopted. The future of building management lies in embracing these innovations, ultimately leading to more sustainable and efficient buildings.

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