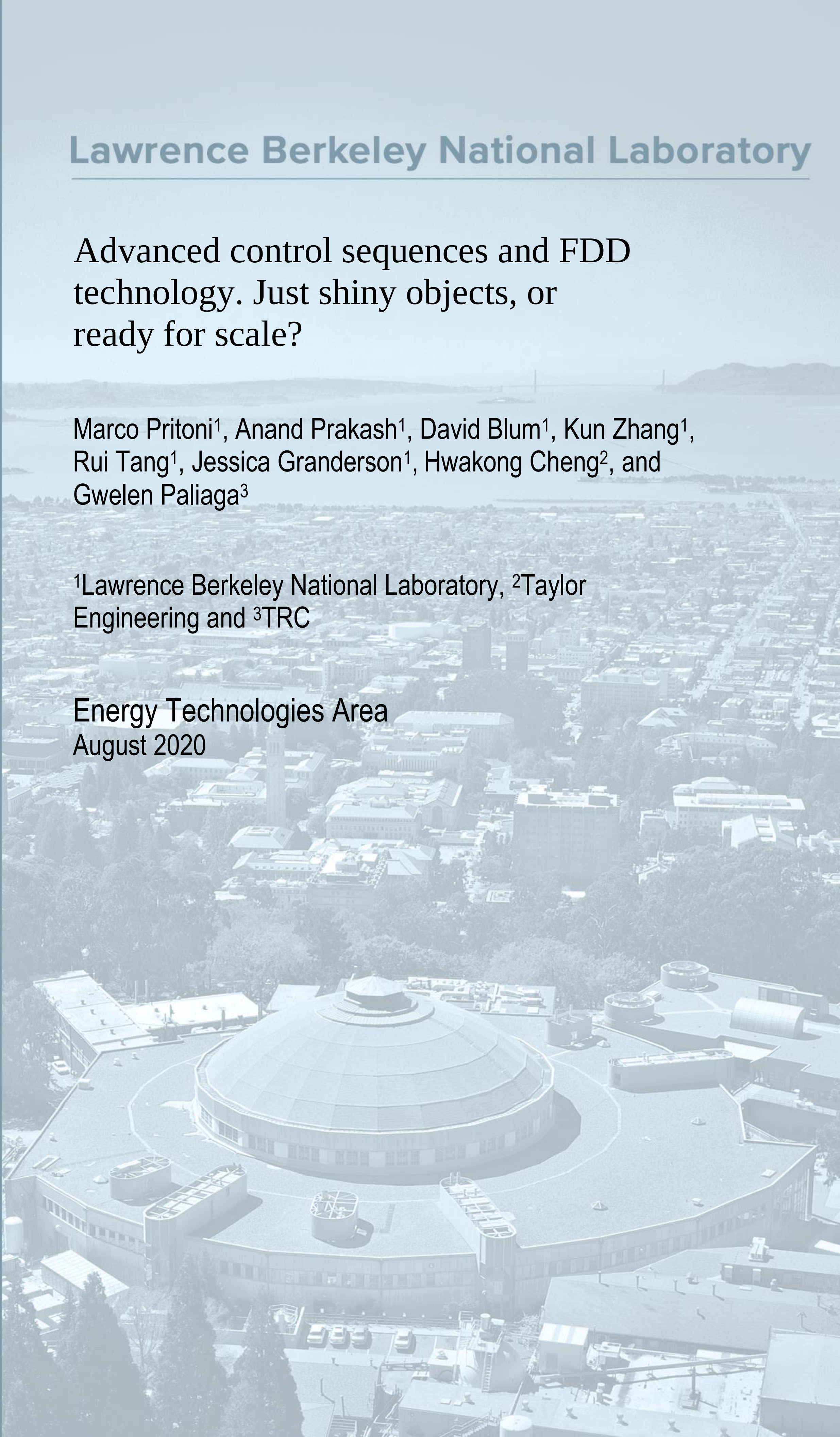
Advanced control sequences and FDD technology. Just shiny objects, or ready for scale?

Pritoni, Marco
Prakash, Anand
Blum, David
et al.

2020-08-01

Lawrence Berkeley National Laboratory



Advanced control sequences and FDD technology. Just shiny objects, or ready for scale?

Marco Pritoni[1], Anand Prakash[1], David Blum[1], Kun Zhang[1], Rui Tang[1], Jessica Granderson[1], Hwakong Cheng[2], and Gwelen Paliaga[3]

[1]Lawrence Berkeley National Laboratory, [2]Taylor Engineering and [3]TRC

Energy Technologies Area
August 2020

Advanced control sequences and FDD technology. Just shiny objects, or ready for scale?

Marco Pritoni, Anand Prakash, David Blum, Kun Zhang, Rui Tang, Jessica Granderson,
Lawrence Berkeley National Laboratory
Hwakong Cheng, Taylor Engineering
Gwelen Paliaga, TRC

ABSTRACT

Innovations in commercial building control sequences (ASHRAE guideline 36) and fault detection and diagnostics (FDD) technology have the potential to transform existing building operational efficiency by realizing whole-building level savings on the order of 15% and higher. However, several technical and market barriers related to up-front estimation of achievable savings, verifying implementation, and ensuring persistence are slowing down their adoption as a core offering through diverse owner-funded initiatives and rate-payer funded programs. This paper describes a suite of solutions to overcome these barriers to program delivery of advanced HVAC controls integrated with FDD energy management and information system (EMIS) technology. First, the Guideline 36 conformance test offers an automated method to confirm correct sequence implementation by the manufacturer, before field deployment. A successful test of a controller was conducted using a new manufacturer-independent hardware-in-the-loop testbed demonstrating the viability and scalability of this approach. Second, the Guideline 36 energy savings calculator uses modeling paired with high-level user inputs to estimate building-specific savings potential, target cost effective implementation and minimize uncertainty. Initial results indicate the baseline control sequences significantly impact energy savings, however, as much as 50% savings may be possible for the worst-case baseline scenario. Third, a functional specification provides minimum recommended EMIS-FDD capabilities, and best practices to integrate the technology into organizational practice and ensure that advanced control sequences provide persistent savings.

Introduction and Background

Emerging as an industry in the 70’s and growing significantly during the ‘80s and ‘90s, with the introduction of microcontroller-based technology, the building controls industry has been slow to innovate and to use standardized solutions, in the last two decades (Pritoni, 2019). While some progress has been made in adopting standard communication protocols, such as BACnet[1], vendors still use proprietary solutions for the implementation of the “sequences of operation” (SOO), that is the logic that determines the coordinated operation of all the components in a building (Pritoni et al., 2018). These sequences are necessary since HVAC systems for large buildings are typically custom-designed and each one is unique in terms of components and configuration. These SOOs are commonly written in a vendor-specific language by the control contractor when the system is installed. The control programs are coded on site without quality control procedures, commonly used in software and hardware developed for

---

[1] BACnet is a standard communication protocol for Building Automation and Control Networks developed and maintained by ASHRAE:

industrialized products (e.g., a control board for a packaged HVAC unit). As a result, the energy efficiency of these SOO is highly dependent on programmer skills, programmer understanding of the building systems, proper commissioning and timely update in case of operational changes. More importantly, there seemed to be a lack of shared knowledge on how to specify "best-in-class" SOOs, independently from the control language they are coded in.

To respond to this last need, a research committee at ASHRAE[2] recently developed Guideline 36 (G36) (ASHRAE, 2018), with the purpose of "providing uniform sequences of operation for heating, ventilating, and air-conditioning (HVAC) systems that are intended to maximize HVAC system energy efficiency and performance, provide control stability, and allow for real-time fault detection and diagnostics".[3] In addition, in the last few years, several new Fault Detection and Diagnostic (FDD) software platforms have become available on the market (Granderson et al, 2018). These software products can be used to verify that the performance of "optimized" sequences is not deteriorating due to faults or other issues.

Table 1. Gaps and solutions addressed in this paper

#	Gap	Stakeholder Impacted	Solution
1	No standard performance validation method for SOO	Control Vendor, G36 committee	G36 Performance Validation Method and Testbed
2	Unknown savings for a specific building configuration	Building Owner/Manager, Engineering Firm	G36 Energy Savings Calculator
3	Unclear requirements for FDD tools	Building Owner/Manager, FDD provider	FDD Specification Guide for G36

While these technologies (i.e., G36 sequences coupled with FDD) have a large potential for delivering energy savings and better indoor environmental quality in buildings, there is no clear path to make them a scalable solution in the market, yet. A CEC-funded project led by Taylor Engineering in partnership with Lawrence Berkeley National Laboratory (LBNL), TRC Energy Services and Integral Group is set to tackle some of these challenges. The project will address technological and market challenges. From a technology standpoint, the project will validate the commercial viability and scalability of Best-in-Class controls retrofits in existing commercial buildings based on G36 sequences. From a market perspective, the project will demonstrate a new delivery mechanism for control systems upgrades with close collaboration with industry, utility, and other partners to address California's need for cost-effective energy and carbon reductions. A companion paper in these proceedings (Paliaga G. et al, 2020) describes the market transformation aspect of the project. This paper explores a set of solutions developed by the research team to bridge three key gaps that hinder the rapid deployment of G36

---

[2] ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers. https://www.ashrae.org/

[3] See definition of the purpose of the standard here: https://www.ashrae.org/technical-resources/standards-and-guidelines/titles-purposes-and-scopes

sequences in several buildings. These gaps and solutions are listed in Table 1 and detailed in the corresponding sections of the paper.

Guideline 36 Performance Validation Method and Testbed

ASHRAE G36 establishes a set of standardized high-performance sequences of operation. In order to achieve the intended performance, the sequences must be translated and programmed accurately in the Building Automation System (BAS) controllers. The long-term opportunity is that standardizing these sequences will allow for a more efficient product delivery mechanism where the sequences are programmed and tested centrally by each manufacturer, and then distributed to their dealers/installers/integrators. This approach would minimize the need for each installer to re-interpret and program the sequences, reduce risk of errors, and reduce the time required for commissioning in the field. To achieve this goal, a performance validation method is needed to provide independent confirmation that each manufacturer has programmed the Guideline 36 sequences accurately. A standardized method of test would also avoid the need for manual interpretation (and the associated human variability) that is required with typical functional testing[4] approaches by automating the inputs and the range of expected responses.

The goal of this effort is to prototype an automated test that provides standardized, repeatable, and objective validation that programming accurately conforms with the requirements of Guideline 36. The platform needs to be generic so that it can be integrated with controllers from any manufacturer.

While different approaches are possible to define the boundaries of the system to be tested, the team decided to test programming on a physical controller using software to simulate the environment rather than connections to physical devices and sensors. Control inputs (or sensor feedback, e.g. temperature and flow) would be simulated using overrides over a network connection, with the controller responses (outputs) similarly monitored in software. Use of a network connection using a standardized communication protocol, like BACnet (ASHRAE, 2019) allows for the simulation platform to be generic and compatible with controllers from various manufacturers. The software environment also provides flexibility to simulate different systems and system options relatively simply. It also provides a relatively simple means to revise and repeat testing with new updates to the guideline and associated programming. This test approach focuses on the programming only and would not address issues in real practice such as point-to-point testing, sensor calibration, or control loop tuning.[5] This approach best addresses the core need for the performance validation method with a practical and reasonable level of effort to test different system options, and with flexibility to repeat testing as necessary with future update cycles to Guideline 36.

The testbed and test procedure were developed to be: 1) **fully automated** (execution of the test does not need user intervention); 2) **repeatable and consistent** (every iteration of the test must return the same results); 3) **vendor agnostic** (compatible with controllers from all manufacturers); 4) **low cost**; 5) **user friendly** (test scripts fed into software should be understandable in plain English).

---

[4] Test of the dynamic function and operation of equipment and systems using manual (direct observation) or monitoring methods. https://www.energy.gov/sites/prod/files/2014/07/f17/commissioning_fed_facilities.pdf

[5] Additional steps in the process of commissioning a control system for a building.

The architecture of the testbed prototyped is illustrated in Figure 1. Yellow indicates the components that are provided by the manufacturer (i.e., controller, control program and point map); blue indicates the English version of G36 developed by the ASHRAE committee, red represents the conformance test script and the test sheet developed by the research team (in the future it should be developed by the testing entity).[6] The left part of the diagram shows the program loaded on the controller and the communication between components of the testbed:

- **Control program**: This is what is tested for conformance with Guideline 36.
- **Controller**: It hosts the control program. The controller is required to communicate via BACnet with the computer and/or router.
- **Computer**: The computer running the test.
- **Local network**: Both the controller and computer are connected to the same local network to avoid requirements of advanced BACnet routing devices such as a BACnet router or a BACnet/IP Broadcast Management Device (BBMD).[7] When necessary (e.g., when the controller communicates over BACnet/MSTP but not BACnet/IP) a BACnet router can be used.

The right side of the diagram shows the computer-hosted software components of the testbed:

- **Point-map**: Input file that matches generic point names standardized in the test script to vendor-specific BACnet object names.
- **Test sheet**: Input file that contains the vendor-independent test for a specific sequence.
- **Guideline36_conformance_test**: The software that interfaces with the controller and runs the test.
- **Outputs**: A CSV file containing the results of the test, in the form of time-series values of each of the relevant variables. These same time series values and other software messages (e.g., warnings) are also printed on the command line interface. A database to store the results and a web interface are considered for future work.

The key component of this approach, the "test sheet", is developed by selecting sections of the Guideline 36 sequences, interpreting them, and conceptualizing a series of functional tests using setpoint and signal feedback overrides that will test the breadth of the sequence implementation under evaluation. This is very similar to the way functional tests are presently generated for testing systems in the field. For each test step, a series of controller inputs, expected controller outputs, and test termination conditions are defined. The changing inputs denote the changing environment (e.g., increase in zone temperature). The test termination conditions define the conditions that end a test step. Test termination conditions can be based on time (e.g. set inputs and run for 10 minutes) or based on an output variable whose value changes over time (e.g. set inputs and wait until cooling loop output is at least 50%). The expected output values for each of the output variables at each step are determined based on expert interpretation of Guideline 36. "guideline36_conformance_test" is the script that performs the validation of the Guideline 36 sequence loaded onto a controller. It is open source software developed in Python 3, and it uses the BAC0 Python library to communicate with the BACnet controller available at a public github repository.[8]

---

[6] While unclear what entity should perform these tests, a successful model could be to use certified labs similar to BACnet Test Labs (https://www.bacnetlabs.org/) for BACnet controllers.

[7] http://www.bacnet.org/Tutorial/BACnetIP/sld007.html

[8] https://github.com/LBNL-ETA/guideline36_conformance_test

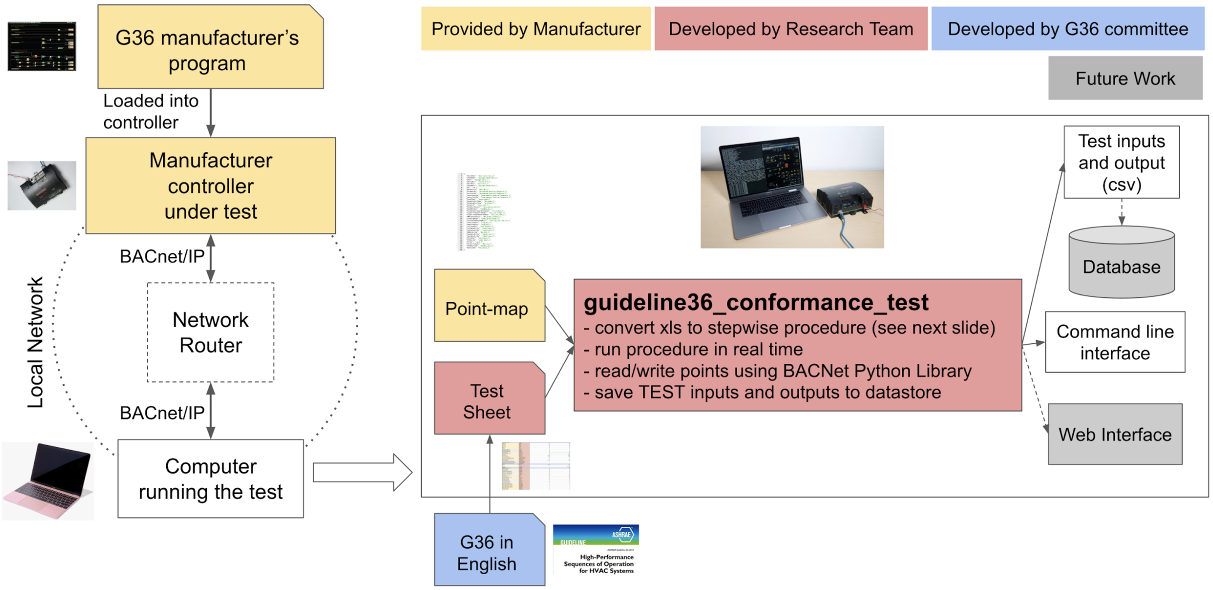


Figure 1. Architecture of the prototype testbed developed by the research team

The method and testbed were tested with one controller from one manufacturer hosting a simple VAV-box sequence from G36. After a few iterations in refining the Python script and the control program, the controller was able to pass the test (Figure 2). The research team also simulated a controller programming error that caused the test to fail.

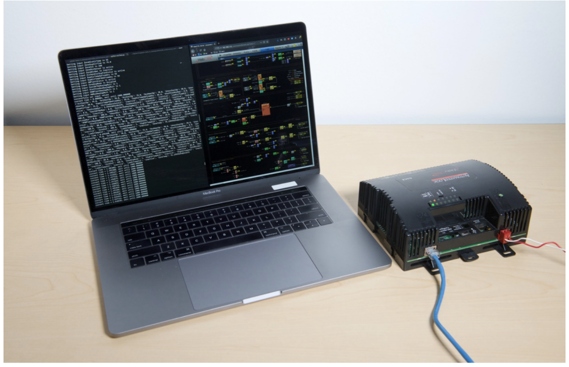


Figure 2. Test in progress. On the left the computer used to host the software. On the right the controller under test. On the computer screen are visible the outputs from the controller (left) and the controller program (SOO) that is running on the controller.

Guideline 36 Energy Saving Calculator

Retrofitting existing HVAC system controls to G36 sequences has a large potential for energy savings in buildings. However, it is difficult to estimate the energy savings of the control retrofits accurately and the process of doing so can be costly. Moreover, the costs of determining the opportunity for retrofit and the implementation of the retrofit itself needs to be justified by the energy and cost savings. For these reasons, the project team designed and implemented the G36 energy savings calculator, that is meant to serve as an early screening tool to provide energy savings estimates for control retrofits of existing buildings to G36 sequences at little cost. The calculator can be used to support utility incentive programs and for engineer use in project design.

To estimate savings for a given case, the following two sets of scenarios need to be modeled for that case:

1. A G36 scenario which represents the advanced control sequences implemented as described in the G36
2. A baseline scenario representing the existing controls condition.

However, two challenges exist in specifying such a case. The first challenge is that the baseline scenario may have a variety of different combinations of control sequences that differ from G36. Examples include duct static pressure reset, supply air temperature reset, and zone airflow control strategies. In addition, for a given control sequence, individual control variables related to that sequence can vary, such as values of static pressure setpoints and supply air temperature setpoints, which can influence savings. The second challenge is that the difference in operation of the two scenarios will also depend on factors related to the design and operation of the building and system itself. Examples include envelope characteristics, internal loads schedules, occupancy behavior and climate zones. This is particularly due to the ability for G36 to more efficiently handle load diversity throughout the zones. Other examples include the equipment efficiencies of the air distribution, heating plant, and cooling plant systems. Given these two sets of factors (baseline control sequences and variables and building design characteristics) that influence the configuration of a particular case, it is necessary to identify a key subset of configuration parameters for users to choose from.

The design of the G36 energy savings calculator is such that it is made up of a user interface front-end, that takes the form of an Excel spreadsheet (Figure 5), and data processing back-end, which takes the form of a database holding results from a wide range of pre-run parametric simulations The user interface allows selection of baseline control strategies along with a number of additional factors such as high-level building characteristics and climate. These selections indicate which of the simulation results contained in the back-end to compare for savings estimation.

A prototype implementation of the savings calculator was based on the following design principles:

1) The building envelope and VAV system model is representative and detailed enough so that the SOO differences between the baseline and G36 can be visible in the results.
2) As the number of the control variables increases, the number of combinations of variables increases substantially and, therefore, so does the number of simulations. For this reason, the simulated control variables are selected based on their anticipated impact on energy savings for the real system.
3) In order to run a large set of simulations automatically, a simulation workflow was designed to streamline the evaluation of different cases (Figure 3).

The system selected for this prototype is a multi-zone (5 zones) VAV system and the model leverages the existing implementation of G36 sequences in the Control Description Language (CDL) as well as the underlying physical model of the building envelope and HVAC system in Modelica, developed as part of the Open Building Control project (Wetter et al., 2018).

CDL is a subset of the Modelica programming language[9] that can be used to specify control sequences in computer code that can be used in dynamic simulation models, used directly in real buildings or translated to proprietary Building Automation Systems (BAS), and used for verification during the control commissioning process. The baseline sequences representing conventional cases for the savings calculators were also implemented using CDL. The building envelope and VAV system were modeled in Modelica and formed a base dynamic model over which various control implementations could be overlaid. The envelope was modeled as a typical five-zone model (north, east, south, west and core zones) with detailed heat balance in the zones, the VAV system was modeled with explicit representation of pressure-flow relationships and specification of actuator control signals, and the heating and cooling plant were ideally modeled with constant efficiencies More details on individual component model implementations can be found in Wetter et al. 2014 and related information in the Users Guide of the Modelica Buildings Library. Three prominent strategies were investigated in this prototype: static pressure reset, supply air temperature reset, and zone airflow control with varying zone minimums. The research team also determined three levels of configurations for each variable: Base, Mid and G36. Table 2 shows a summary of the control variables at each level with the strategies included. The nine cases at the bottom of the table represent combinations of variables controlled using the strategies in the table above.

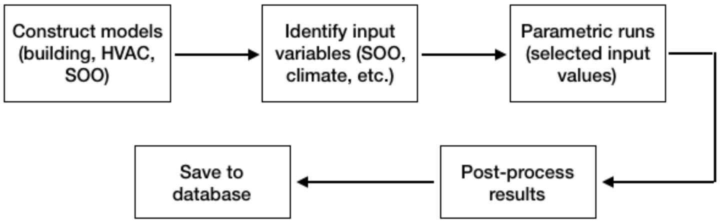


Figure 3: Designed simulation workflow for the savings calculator

Figure 4 shows the HVAC electricity use of the nine cases simulated in a Chicago, IL climate. We can see from the left plot of the figure that the Base case uses the most HVAC energy, the G36 uses the least energy while the Mid case energy use is between that of the Base and the G36 case. The plot on the right shows the energy uses of the six other combinations of the control variables and we can see that their energy use is between that of the Base and Mid case. We can see that the highest G36 energy savings percentage is more than 50 % against the Base case. The G36 sequences consume less energy than the other cases for heating, cooling and fan. The zone airflow rate modulation and static pressure reset strategy impact the fan energy use. The zone airflow rate and supply air temperature reset strategy impact both the heating and cooling energy use. This shows that the three control strategies the researchers have investigated impact the HVAC energy use quite significantly. Overall, the G36 energy savings are fairly substantial, and close to the results reported in (Pang et al., 2017).

---

[9] https://www.modelica.org/

Table 2: Example of simulated control variables and combinations of cases

Control variables	**Base**	**Mid**	**G36**
Static pressure	Constant (A1)	Limiting zone (A2)	Trim & Respond
Supply air temperature	Constant (B1)	Linear with Outside Air Temperature (B2)	Trim & Respond
Zone airflow	Single maximum (C1) with Vmin = 30%Vmax	Single maximum (C2) with Vmin = 20%Vmax	Dual maximum
Cases: Base, Mid, G36, A1B1C2, A1B2C1, A1B2C2, A2B1C1, A2B1C2, A2B2C1			

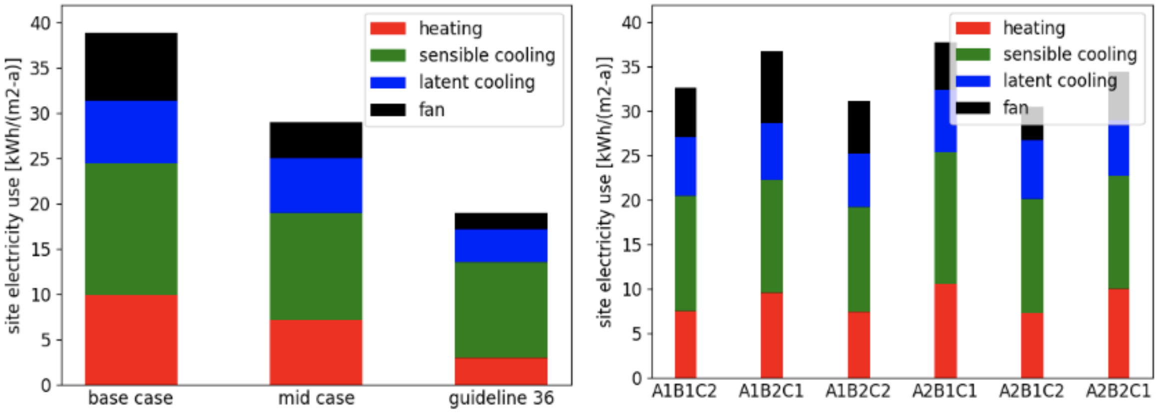


Figure 4: Energy savings using the prototype of the G36 Energy Savings Calculator for a 5-zone system in Chicago, IL

Finally, Figure 5 presents the prototype implementation of the G36 Savings Calculator, with data populated from the simulations described above. In the calculator, Table 1 (Fig 5) allows the user to select a combination of individual control sequences as a baseline configuration. Table 2 (Fig 5) presents a description of the control scenario selected for each control sequence. Table 3 (Fig 5) presents the energy consumption and savings estimated for the specified configuration. Table 4 (Fig 5) presents a summary of available configurations.

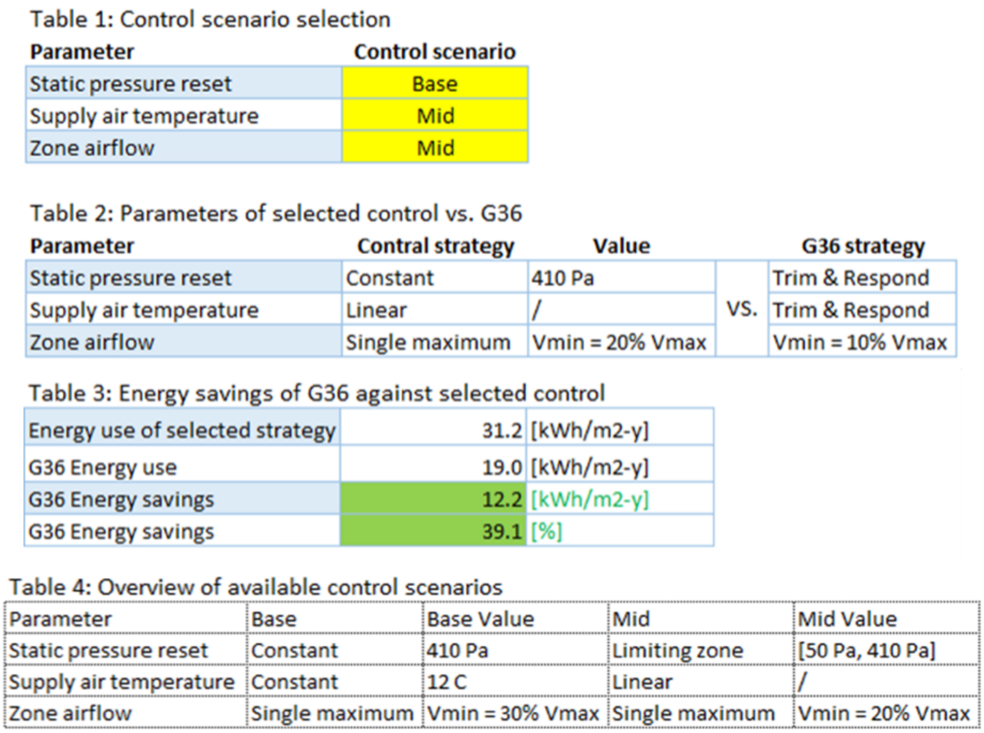


Table 1: Control scenario selection

Parameter	Control scenario
Static pressure reset	Base
Supply air temperature	Mid
Zone airflow	Mid

Table 2: Parameters of selected control vs. G36

Parameter	Contral strategy	Value		G36 strategy
Static pressure reset	Constant	410 Pa	VS.	Trim & Respond
Supply air temperature	Linear	/		Trim & Respond
Zone airflow	Single maximum	Vmin = 20% Vmax		Vmin = 10% Vmax

Table 3: Energy savings of G36 against selected control

Energy use of selected strategy	31.2	[kWh/m2-y]
G36 Energy use	19.0	[kWh/m2-y]
G36 Energy savings	12.2	[kWh/m2-y]
G36 Energy savings	39.1	[%]

Table 4: Overview of available control scenarios

Parameter	Base	Base Value	Mid	Mid Value
Static pressure reset	Constant	410 Pa	Limiting zone	[50 Pa, 410 Pa]
Supply air temperature	Constant	12 C	Linear	/
Zone airflow	Single maximum	Vmin = 30% Vmax	Single maximum	Vmin = 20% Vmax

Figure 5. Excel front-end of the G36 savings calculator.

FDD Functional Specification

While G36 sequences have the potential to save a large amount of energy, their operation is likely to degrade if not proactively monitored. FDD tools are increasingly implemented through software that pulls data from the BAS to implement a monitoring-based commissioning process (MBCx). MBCx is a systematic process for investigating, analyzing, and optimizing the performance of building systems through the identification and implementation of low/no cost and capital-intensive facility improvement measures and ensuring their continued performance. This same process can be used to monitor the correct operation of G36 sequences.

Today's FDD offerings feature large libraries of fault detection algorithms and complementary analytics, reporting and visualizations that can be applied across many systems and available data points (Granderson et al, 2018). Given the variety of features available in the market, it is useful to define a set of minimum recommended capabilities for owners who wish to procure FDD technology in support of persistent operational efficiency. The corresponding FDD functional specification that was developed in this work was created based on the authors' subject matter expertise, familiarity with best practices uses of FDD in the field, and information obtained from FDD publications and technical reports. The document can be used as the basis of a project- or organization-specific specification, or request for proposals (RFP).

The functional specification suggests minimum recommended base capabilities in the following categories:

- building systems addressed: for example, chilled water and boiler plants, packaged rooftop units, air handling units, and terminal units are critical, while systems such as lighting and plug loads could be considered in expanded implementations that go beyond base capabilities.

- detectable faults: for example, sensor errors/faults, stuck valves and dampers in water- and air-side systems, scheduling of HVAC, hunting or cycling, manual overrides, chilled water supply temperature reset, under or over economizing of air-handling unit and packaged rooftop unit, high VAV minimum supply air flow are critical, while faults such as building pressurization requirements, recirculation of exhaust air into air handler intake plenum, and faults associated with the control and operation scheduling of lighting loads could be considered in expanded implementations that go beyond base capabilities.
- fault diagnosis: recommended actions for detected faults and fault prioritization are critical, while capabilities such as the ability to add notes to faults and assign a responsible party for follow up could be considered in expanded implementations that go beyond base capabilities.
- complementary analytics: for example, visualization and plotting of time series operational and energy consumption data, and key performance indicator tracking for parameters (such as building level energy use intensity) are critical, while capabilities such as measure-level savings estimation, cross-sectional or longitudinal benchmarking and load prediction could be considered in expanded implementations that go beyond base capabilities.
- architecture, data integration, data export/reporting: for example, ability of integration with non-legacy vintages of major meter and BAS providers via common protocols, cybersecurity provisions aligned with organizational IT requirements, provision of an API (application programming interface) and data reporting are critical. Capabilities such as integration with specific applications, e.g., computerized maintenance management systems (CMMS), meter visualization and energy information systems (EIS) could be considered beyond base capabilities.

While identifying the specific functional capabilities desired for an FDD technology is important, it is just as important to integrate FDD into an organization's processes and business practices – an FDD tool that is not well-utilized will have limited benefit. Therefore, the specification material is complemented with a discussion of best practices in the planning, procurement, configuration, and implementation phases of FDD use. These best practices span considerations ranging from explicit identification priority faults and systems for resolution once faults are identified, to identification of internal champions, to cost guidelines, MBCx process guidance, and training.

Discussion and Conclusion

In this paper the authors present a set of solutions that address challenges hindering the scalability, rapid adoption, and successful delivery of G36 sequences in commercial buildings. The G36 Performance Validation Method and Testbed is a prototype testbed to validate the implementation of G36 sequences by a manufacturer. The G36 Energy Saving Calculator is a prototype tool to estimate the savings potential due to the implementation of these sequences given a baseline building and control logic. While these are only proofs of concept, the preliminary stakeholder feedback received has been positive and useful to define the next steps of each effort.

For the Performance Validation Testbed, an additional vendor is interested in testing a controller using this approach, which will be essential to prove the test is vendor-neutral. Indeed, there may be differences in the implementation of SOO (e.g., different control variables, internal level logic such as setpoints or dead-bands) by different manufacturers, that will need to be explored in future work. Moving forward, it is important to understand what organization should be responsible for further developing this testbed and for maintaining it up to date with the frequent updates of the ASHRAE G36 committee. Several upgrades to the software will be needed to make it a stable and usable testing platform:

1) The addition of a simple web-user interface and a database to store the results (Figure 1).
2) The development of test scripts to validate the syntax in point maps and test sheets before the test is initiated.
3) The investigation of the repeatability of tests. Currently the results of repeat tests are generally consistent, but the run times are not; they vary with each execution. This could be due to network and/or processor delays and requires further investigation.
4) The development of a simple interface for generating the point map, possibly another Excel sheet. This will simplify the mapping process for manufacturers.

In the long term, the vision is that G36 sequences should be specified using a "generic control language" that is machine-readable, in addition to the English description. Each manufacturer could then develop compilers to transform these sequences into their own proprietary control code. Such a process would allow consultants to use "machine-readable specifications", instead of plain English in the bid process and streamline subsequent implementation phases. A LBNL project titled Open Building Control (OBC; Wetter et al., 2018) is proposing a candidate generic language referred as "Control Description Language" (CDL).[10] This language was recently approved by ASHRAE as a proposed standard[11]. However, the CDL implementation of G36, much like any manufacturer's, will need to be properly validated. This is particularly so if it is to be the reference implementation from which other manufacturers might theoretically compile their own code. There may therefore be research synergy in developing a full suite of test scripts for the CDL reference implementations and using the guideline36_performance_test program to execute the validation. Beyond the logistical issues of fleshing out the test bed and writing scripts for the entirety of G36, the team also sees a need to better define how the test scripts should be prepared (e.g. should they be modularized to test discrete sections of logic, or test complete combinations of programs) and administered through a certification process. The development of an industry-accepted performance validation method will require significant stakeholder input, particularly from manufacturers and the ASHRAE Guideline 36 project committee.

The Savings Calculator will be important to scaling the delivery of G36 upgrades through programs, helping with estimation of potential savings and cost effectiveness. The stakeholders recommended (1) which additional control strategies to prioritize; (2) which additional building model inputs to prioritize. Based on this feedback the team decided to focus on these next steps:

1) Add minimum outdoor air control in the control variables
2) Simulate variability of occupancy schedules (including number of hours per day, stochasticity, and magnitude of peak loads etc.)

---

[10] https://obc.lbl.gov/specification/cdl.html

[11] ASHRAE winter conference 2020 - details to come.

3) Simulate variability of internal gains schedules (including number of hours per day, stochasticity, and magnitude of peak loads etc.)
4) Simulate different California climates
5) Simulate variability of space types/zone groups (e.g., office, meeting room, corridor etc.)

Another important step is using field data to validate the magnitude of savings estimated and point out where the simulations fail to accurately capture reality. Field data collected by this and other projects should be used for this validation.

The FDD Functional Specification provides minimum recommended functionalities and capabilities for the building owners and managers. Similar to the previously published EMIS specification template (Better Buildings, 2015), used to great success by owners and utility program managers, these specifications are meant for people considering procurement of FDD technology for commercial buildings. Eventually these FDD specific functions noted here in this work will be merged into the EMIS document.

Beyond the technical challenges addressed here, the authors acknowledge that G36 and FDD tools provide an opportunity for a profound transformation in this market that cannot be realized without addressing market barriers (Paliaga G. et al, 2020).

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DEAC02-05CH11231. The work was funded by Taylor Engineering through the California Energy Commission Electric Program Investment Charge (EPIC) Program, Solicitation Grant Funding Opportunity Number: EPC-GFO-16-304, entitled “Smart Building Controls and Diagnostic Upgrades for California”.

References

American Society of Heating and Air-Conditioning Engineers (ASHRAE). (2018). “GUIDELINE 36-2018 -- HIGH-PERFORMANCE SEQUENCES OF OPERATION FOR HVAC SYSTEMS”. Standard by ASHRAE. 2018. https://www.techstreet.com/ashrae/standards/guideline-36-2018-high-performance-sequences-of-operation-for-hvac-systems?product_id=2016214

American Society of Heating and Air-Conditioning Engineers (ASHRAE). (2019). “STANDARD 135-2016, BACNET™ -- A DATA COMMUNICATION PROTOCOL FOR BUILDING AUTOMATION AND CONTROL NETWORKS”.

Better Buildings. (2015). “Energy Management Information Systems (EMIS) Specification and Procurement Support Materials” Report retrieved from https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/emis_proc_spec_BBA_FINAL_021815_508.pdf

Granderson, J., Lin, G., Singla, R., Mayhorn, E., Ehrlich, P., Vrabie, D., Frank, S. (2018). “Commercial Fault Detection and Diagnostics Tools: What They Offer, How They Differ, and What’s Still Needed”. Report retrieved from https://doi.org/10.20357/B7V88H

Paliaga G., R. Singla, C. Snaith, S. Lipp, D. Mangalekar, M.Pritoni. (2020). Re-Envisioning RCx: Achieving Max Potential HVAC Controls Retrofits through Modernized BAS Hardware and Software. ACEEE Summer Study 2020.

Pang, X., Piette, M. A., & Zhou, N. (2017). Characterizing variations in variable air volume system controls. Energy and Buildings, 135, 166–175. https://doi.org/10.1016/j.enbuild.2016.11.031

Pritoni M., Weyandt C., Carter D., Elliott J. (2018). "Towards a Scalable Model for Smart Buildings". ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA. 2018.

Pritoni M. (2019). "The Past and the Future of Building Automation Systems". Presentation at the Building Efficiency for Sustainable Tomorrow workshop. 01 October 2019.

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

Wetter M., J. Hu, M. Grahovac, B. Eubanks and P. Haves. (2018). "OpenBuildingControl: Modeling feedback control as a step towards formal design, specification, deployment and verification of building control sequences". Proc. of Building Performance Modeling Conference and SimBuild, p. 775–782, Chicago, IL, USA, September 2018.