Development and Verification of Control Sequences for Single-Zone Variable Air Volume System Based on ASHRAE Guideline 36

Kun Zhang, David H. Blum, Milica Grahovac, Jianjun Hu, Jessica Granderson, Michael Wetter
Building Technology and Urban Systems Division
Lawrence Berkeley National Laboratory
Berkeley, CA, USA
`{kunzhang,dhblum,mgrahovac,jianjunhu,jgranderson,mwetter}@lbl.gov`

Abstract

This paper presents work on the development and verification of ASHRAE Guideline 36-2018 control sequences for single-zone variable air volume air-handling unit (AHU) systems. The Control Description Language, a subset of the Modelica Language, is used to implement those advanced control sequences. The sequences address control for components such as the economizer, supply air temperature setpoint reset, fan speed control, and zone heating/cooling states determination. Each component sequence is validated in open-loop tests and then used to compose a single comprehensive controller. This controller is also first validated in open loop and then tested in closed loop with an AHU system and building envelope model constructed using the Modelica Buildings library. The Guideline 36 controller is compared with a conventional control strategy applied to the same AHU and building model. Annual simulations show that the Guideline 36 control sequences yield 17.3 % of annual HVAC energy savings against the conventional control strategy in this case study.

Keywords: Control, VAV, ASHRAE Guideline 36, Buildings, HVAC

1 Introduction

The Heating, Ventilation and Air Conditioning (HVAC) control industry has not yet had a standard for expressing control sequences of HVAC systems (Pang et al, 2017). The controllers in the market can be generally divided into two types: configurable and programmable. The first type of controller is pre-programmed; it is therefore easy to install and commission. However, the embedded control logic is often overly simplistic, resulting in a compromise of thermal comfort and energy efficiency required by evolving energy standards and building codes. The second type is fully programmable (Hydeman, Taylor, & Eubanks, 2015). Yet, due to a lack of standard high-efficiency sequences, the implemented control scheme of the HVAC system is often project-specific. Therefore, significant resources are required to engineer, specify, program and commission each project. It is also common that the implemented control sequences are sub-optimal and error-prone, which leads to varied building operational efficiency and performance (Hydeman et al, 2015).

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has initiated projects related to high-performance control sequences for HVAC systems through its Research Projects 1455 (Taylor Engineering, 2014) and 1711. A first version of ASHRAE Guideline 36-2018 (G36) (ASHRAE, 2018) was published upon completion of the Project 1455. The control sequences included in the G36 are based on the best-in-class industry practices. The guideline aims at reducing energy consumption and improving thermal comfort and indoor air quality of buildings. It also provides potential to reduce the time of the engineering, specification, programming and commissioning process (ASHRAE, 2018).

Implementing the advanced control scheme as described in the Guideline 36 does present its own challenges, due to the complexity of the sequences. The English language description can be ambiguous, and its interpretation to implement the sequences in a programming language is not straight-forward.

The G36 2018 version includes control sequences for the air distribution for single-zone and multi-zone variable air volume systems. The multi-zone system has been implemented in the Control Description Language (CDL) and reported in (Wetter et al, 2018). This paper focuses on the implementation of the G36 control sequences for Single Zone Variable Air Volume (SZVAV) systems using CDL (Wetter et al, 2018a). CDL is a subset of Modelica with its own set of data types and elementary blocks. It intends to allow for implementation of control sequences in computer code that can be used in real buildings, assessed through explicit simulation, and reused for verification tests during the commissioning process. CDL was developed

zone state (at the time 2700s the zone state is changed from heating to cooling).

3 Case study

To test the controller in a closed-loop scenario, a model is created to integrate the controller with a SZVAV AHU system and a single-zone building envelope model. Measurements of the building air temperature, supply air temperature, return air temperature, and mixed air temperature are fed back to the controller to close the control loop (see Figure 10). Other important parts of the model include the weather data and occupancy schedules.

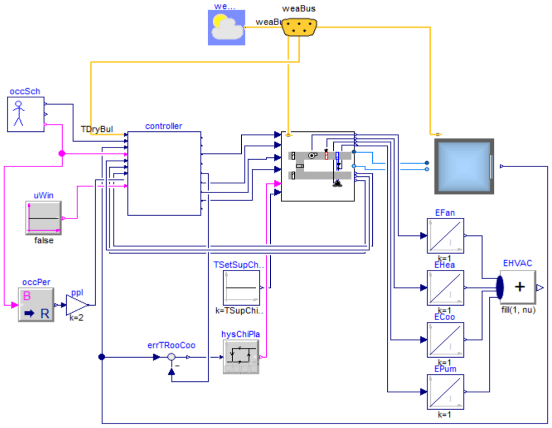

Figure 10. Closed-loop control model with the building, AHU and G36 controller.

The details of the building and AHU model are illustrated in the subsections below, and the performance of the G36 controller is compared with a conventional Baseline controller in Section 4.

3.1 Building envelope model

The building envelope model used for this case study is from the model Buildings.Air.Systems.SingleZone.VAV.Example.BaseClasses.Room. It uses an instance of Buildings.ThermalZones.Detailed.MixedAir to model the transient heat conduction within the building constructions and longwave radiation heat exchange between the surfaces (walls, roof and windows etc.). The heat convection and radiation between the ambient (indoor and outdoor air) and the envelope is also modeled at each time step.

The information of the envelope such as geometry and materials are from the BESTEST case 600, and derived from the EnergyPlus validation project (Henninger & Witte, 2004).

The weather data used in the case study is the DRYCOLD weather data included in the Buildings library, which is the weather used for the BESTEST case studies. It is from the weather station of Denver-Stapleton in Colorado, USA. The occupancy schedule for the building is assumed to be from 8am to 6pm daily, which means that the system is operated based on this schedule. The internal heat gains are modelled as constant gains when the zone is occupied.

3.2 Air handling unit system model

The air handling unit system model from the class Buildings.Air.Systems.SingleZone.VAV.ChillerDXHeatingEconomizer contains a variable-speed supply fan, a heating coil, a water-based cooling coil, and an economizer. The cooling coil is assumed to be served by an air-cooled chiller. The model assumes that pressure drops through the system are lumped into a single component and the cooling coil is a dry coil. The mass flow of chilled water through the cooling coil is controlled by a three-way valve to maintain the cooling supply air temperature setpoint. The cooling coil mixing valve and the economizer dampers are modeled as ideal, i.e., they exactly control a specified ratio of fluid flow through contributing branches.

The fan and pump models are idealized to exactly track the set point for the mass flow rate, and they are from the model Buildings.Fluid.Movers.FlowControlled_m_flow. The details about the fan/pump model are described in (Wetter, 2013).

The design airflow rate for the AHU system is 0.625 m^3/s. The minimum outdoor airflow rate is 0.0144 m^3/s and the design outdoor airflow rate is 0.025 m^3/s. The calculation of the ventilation requirement for the building model is based on ASHRAE Standard 62.1 (ASHRAE, 2016) for an office with reference occupancy density. Note that the G36 controller is capable to adjust the outdoor airflow rate between the minimum and design outdoor airflow based on whether there are occupants in the zone; while the Baseline controller is configured to provide the design outdoor airflow.

The chiller model is Buildings.Fluid.Chillers.ElectricEIR. It is a model of an electric chiller, based on the DOE-2.1 chiller model and the EnergyPlus chiller model Chiller:Electric:EIR (Hydeman et al, 2002). Its nominal Coefficient of Performance (COP) is 5.5. The heating plant is not modelled and we assume it is a geothermal heat pump with a constant COP of 4.0.

3.3 Baseline controller model

The Baseline controller is based on the commonly used single-maximum VAV control with dry-bulb economizer control. During cooling, the fan speed is controlled to maintain the room temperature at the cooling setpoint temperature using a P controller, between a minimum and maximum fan speed. Flow through the cooling coil is controlled to maintain a constant supply air temperature setpoint. During heating, the fan speed is constant at the minimum speed while the heating coil is controlled to maintain the room temperature at the heating setpoint using a P controller. The minimum position of the outdoor air damper ensures enough ventilation flow to meet ASHRAE 62.1

at minimum fan speed. If the outside air dry-bulb temperature is lower than the return air dry-bulb temperature, the economizer opens the damper further to provide cooling of the mixed air to the supply air temperature setpoint as much as possible. During unoccupied times, the zone heating and cooling setpoints are set back and the minimum outdoor air damper position is set to zero.

4 Results comparison

The performance of these G36 and base controllers was compared using identical models for the building envelope, AHU system and weather. Overall, the G36 controller saves 17.3 % HVAC electric energy compared with the Baseline case. The heating energy use for both controllers is nearly equal, with most of the energy savings of the G36 controller associated with the cooling energy. The pump electricity use is minimal for both cases and the G36 controller uses slightly more electricity for the supply fan. Figure 11 shows the breakdown of the monthly energy use for the two controllers with left bars indicating the Baseline controller and right bars indicating the G36 controller. It can be clearly seen that G36 requires less energy use for cooling throughout all the months. In the winter months (December, January and February) G36 consumes 2.6% more heating energy than the Baseline. This small increase could be due to two factors. The first is when near the end of an occupancy period the internal loads are decreasing and the zone switches from cooling mode to deadband. This mode switch increases the SAT setpoint according to Figure 3. For the remaining time the fan is supplying outside air, and the temperature is low outside, heating is briefly used to heat the supply air to the setpoint. This is shown in Figure 14. The second factor is the small amount of increased outside air the G36 control sequence provides during morning heat up, as shown in the upper plot of Figure 13, which adds a small amount of heating load to the coil.

Figure 12 shows the zone temperature profiles during a winter and a summer week along with the zone heating and cooling setpoint. We can see that the zone temperatures are maintained within the heating and cooling setpoint bands by both controllers during these two extreme weeks. In addition, we can see that the zone temperatures are very close to each other in both cases. We actually find that both controllers deliver very similar zone temperatures all year around, with temperature difference within 0.5 K, the same magnitude as the temperature hysteresis settings in the controllers. Using the zone temperature as the thermal comfort indicator, we can conclude that both controllers maintain the thermal comfort in the zone equally close. This means that the G36 controller does not compromise thermal comfort while yielding energy savings.

Figure 13 shows the outdoor airflow during the same two weeks. We can see that the outdoor airflow profiles of the two cases are very similar to each other in winter. During this winter week, the outdoor air temperature is very low as shown by the lime curve in Figure 12, so the controllers restrict the outdoor air fraction to the minimum required for ventilation during heating, as seen in the mornings of each day and use the economizer if any cooling is needed, as seen during the other afternoons in the week. In the summer week, the G36 is capable of lowering the outdoor airflow rate by adjusting the minimum outdoor air damper position based on the fan speed. This reduces excess load on the cooling coil when the outdoor air temperature is higher than the zone temperature. As the Baseline controller assumes no active reset on the minimum outdoor air damper position, excess outdoor air is brought in when the fan speed increases for space cooling.

In Figure 13 we also find that there are sudden jumps in the outdoor airflow profiles, for example, on the afternoon of August 1st (more significant airflow increases for the G36 controller). During that period, the outdoor air temperature becomes lower than the zone temperature setpoint (see the lower plot of Figure 12); both controllers therefore increase the OA damper opening to use more outdoor air to cool down the building. However, the G36 controller simultaneously resets the cooling SAT setpoint up (see the green curve in Figure 15). This results in an increase of the supply airflow rate in order to meet the zone cooling load; however, the G36 controller does so by use of more outside air and without use of any mechanical cooling. On the other hand, the Baseline controller maintains a constant SAT for cooling (see the blue curve in Figure 15), so mechanical cooling is still required to reach the

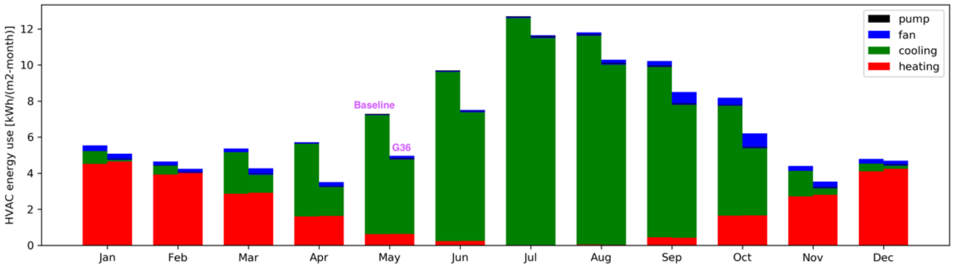

Figure 11. Site HVAC electricity use for each month (Left bars: Baseline; Right bars: G36).

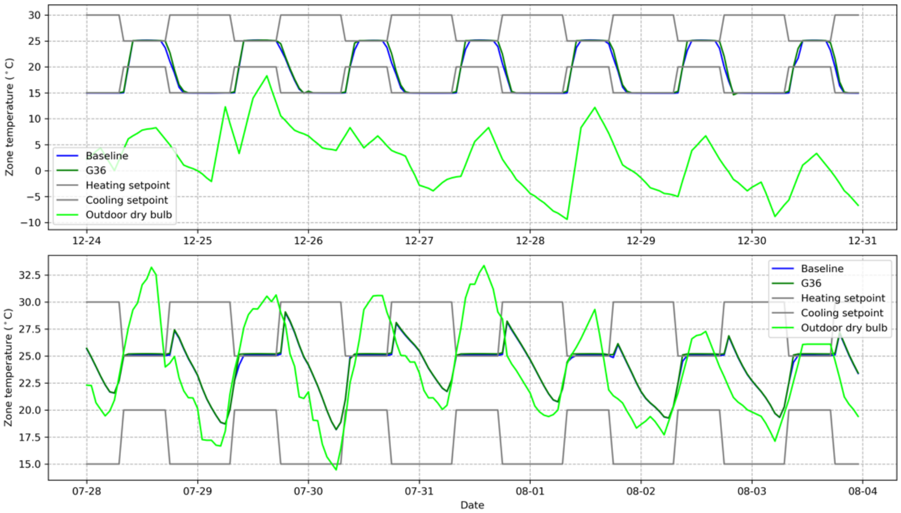

Figure 12. Zone temperature profiles during a winter (top) and a summer (bottom) week

Figure 13. Outdoor airflow rate during a winter (top) and a summer (bottom) week.

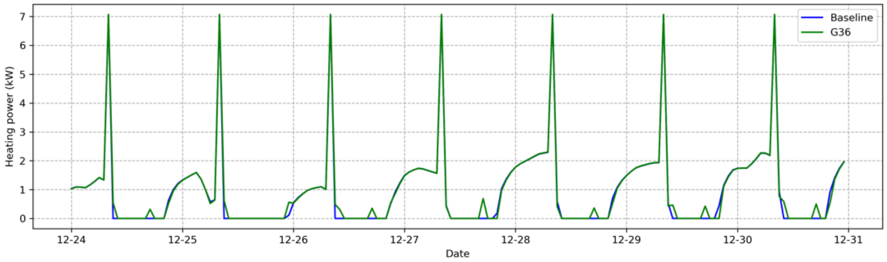

Figure 14. Heating power demand during a winter week.

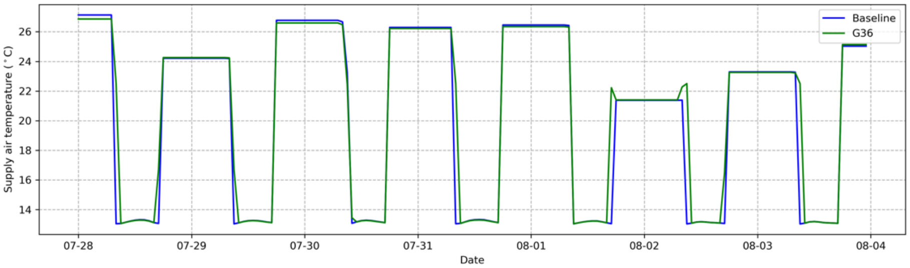

Figure 15. Supply air temperature for cooling in a summer week.

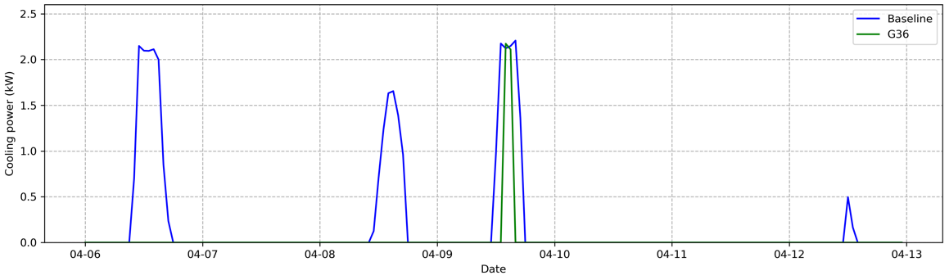

Figure 16. Cooling power demand in a week of shoulder season.

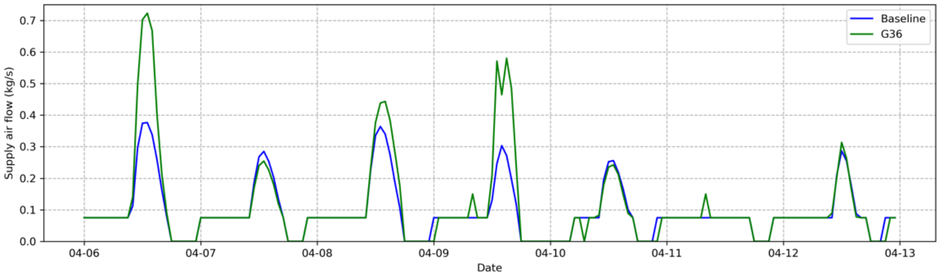

Figure 17. Supply airflow rate in a week of shoulder season.

lower cooling SAT setpoint, even though the economizer is enabled. This shows how the advanced control sequences of the G36 take even more advantage of available free cooling by coordinating the SAT setpoints reset and the economizer operation. This strategy of coordinating the SAT setpoint reset and the economizer operation is the main reason why the G36 controller consumes less cooling energy than the Baseline. The strategy is particularly useful during shoulder seasons. Figure 16 shows the cooling power demand in a week of the shoulder season. We can see that the G36 uses much less cooling energy than the Baseline for this week. Figure 17 shows the supply airflow rate in the same week of the shoulder season as in Figure 16. We can see that the G36 controller has higher supply airflow than the Baseline for the whole week. This is because the G36 controller engages the economizer more often to increase the outdoor airflow to utilize free cooling than the Baseline. This explains why the G36 does not save fan energy as shown in Figure 11.

Finally, it should be noted that the simulation time for each controller was similar, with the Baseline controller at 507 seconds and the G36 at 526 seconds. The simulations were run on a Linux operating system with a 16-core processor (Intel Xeon® CPU X5650 @2.67GHz) and a 32GB memory. In general, the simulation time with different control strategies can be largely dependent on the number of events generated through mode or on/off switching.

5 Discussions and conclusions

This paper presented the work on implementation, validation and application of ASHRAE Guideline 36-2018 control sequences for single-zone variable air volume air-handling unit systems. Those advanced control sequences address control for AHU system components such as the economizer, supply air temperature setpoints reset, fan speed control, and zone heating and cooling states.

The control sequences were implemented using the Control Description Language in a modularized approach, which therefore allows the users to customize the sequences for their needs. Each component sequence was validated in open-loop tests and then used to compose a single comprehensive controller. This controller was firstly validated in open loop and then tested in closed loop with an AHU system and building envelope model constructed using the Modelica Buildings library.

The Guideline 36 control sequences were compared with the conventional control strategy based on single-maximum VAV control. Both controllers were applied to the same AHU and building system in a case study.

Annual simulations show that the Guideline 36 control sequences yield 17.3 % of annual HVAC energy savings against the conventional control strategy. The G36 control scheme can take advantage of free cooling by adjusting the economizer dampers and resetting supply air temperature setpoints; the G36 controller therefore has reduced energy consumption due to cooling. Verification of annual zone temperatures show that both controllers maintain the zone temperature very closely to each other within thermal comfort bands. This shows that the energy savings of the G36 control sequences do not compromise thermal comfort while delivering the energy savings.

It should be noted that the percentage of energy savings shown by the G36 controller in this paper is specific to the selected case study. The energy savings potential is subject to variables such as climate zones, internal heat gains assumption and the baseline control sequences. Future work of this study includes investigating the impact of those variables on the G36 control sequences performance. Validation of the control sequences with measurement data is also important to further verify the implementation of the sequences.

Data availability

All the models and components used in this paper are open-source and can be downloaded from the Github repository https://github.com/lbl-srg/modelica-buildings. The Modelica Buildings branch for the models used in this study is issue1608_compareSZVAV (commit 7c939c0). Table 1 lists the Modelica path of the two closed-loop system models in the case study and the SZVAV package in the Buildings library.

Acknowledgements

This research 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. DE-AC02-05CH11231, and the California Energy Commission's Electric Program Investment Charge (EPIC) Program. We thank Taylor Engineering for their funding of this work through the California Energy Commission's (CEC) Electric Program Investment Charge (EPIC) Program.

Table 1. Models and package used in the paper from the open-source Modelica Buildings library

Name	*Modelica Path*
Baseline system model	Buildings.Air.Systems.SingleZone.VAV.Examples.ChillerDXHeatingEconomizer.mo
G36 system model	Buildings.Air.Systems.SingleZone.VAV.Examples.Guideline36.mo
SZVAV package	Buildings.Controls.OBC.ASHRAE.G36_PR1.AHUs.SingleZone.VAV

References

ASHRAE. (2016). *Ventilation for acceptable indoor air quality*. *ASHRAE Standard*. Atlanta, GA: American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

ASHRAE. (2018). *ASHRAE Guideline 36-2018 High-Performance Sequences of Operation for HVAC Systems* (Vol. 8400). Atlanta, GA: American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

EnergyPlus Development Team. (2019). *EnergyPlus engineering reference: The reference to EnergyPlus calculations*. EnergyPlus Version 9.2. US Department of Energy.

Fernandez, N., Xie, Y., Katipamula, S., Zhao, M., Wang, W., & Corbin, C. (2017). *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction*. Richland, WA: Pacific Northwest National Laboratory Technical Report 25985.

Henninger, R. H., & Witte, M. J. (2004). *EnergyPlus testing with ANSI/ASHRAE standard 140-2001 (BESTEST)*. Washington, D.C.: U.S. Department of Energy.

Hydeman, M., Gillespie, K. L., & Dexter, A. L. (2002). Tools and techniques to calibrate electric chiller component models. *ASHRAE Transactions*, *108 PART 1*, 733–741.

Hydeman, M., Taylor, S. T., & Eubanks, B. (2015). Control sequences & controller programming. *ASHRAE Journal*, *57*(3), 58–62.

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

Taylor Engineering. (2014). *ASHRAE RP-1455: Advanced Control Sequences for HVAC Systems Phase I.* Alameda, CA: Taylor Engineering.

Wetter, M. (2013). Fan and pump model that has a unique solution for any pressure boundary condition and control signal. In *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association, Chambery, France, August 26-28* (pp. 3505–3512).

Wetter, M., Grahovac, M., & Hu, J. (2018a). Control Description Language. *Proceedings of The American Modelica Conference 2018, October 9-10, Somberg Conference Center, Cambridge MA, USA*, *154*, 17–26. https://doi.org/10.3384/ecp1815417

Wetter, M., Hu, J., Grahovac, M., Eubanks, B., & Haves, P. (2018b). OpenBuildingControl: Modelling Feedback Control as a Step Towards Formal Design, Specification, Deployment and Verification of Building Control Sequences. In *2018 Building Performance Modeling Conference and SimBuild, Chicago, IL, September 26-18, 2018* (pp. 775–782).

Wetter, M., Nouidui, T. S., Lorenzetti, D., Lee, E. A., & Roth, A. (2015). Prototyping the next generation energyplus simulation engine. *Proceedings of Building Simulation 2015:14th Conference of International Building Performance Simulation Association, Hyderabad, India, December 7-9*, 403–410.

Wetter, M., Zuo, W., Nouidui, T. S., & Pang, X. (2014). Modelica Buildings library. *Journal of Building Performance Simulation*, *102*(1), 253–270. https://doi.org/10.1080/19401493.2013.765506