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Estimating ASHRAE Guideline 36 energy savings for multi-zone variable air volume systems using Spawn of EnergyPlus

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ABSTRACT

ASHRAE Guideline 36 (G36) publishes high-performance control sequences for Variable Air Volume (VAV) system operation. Retrofitting existing VAV control sequences to G36 promises to have a large potential for energy savings. However, it is difficult to estimate the savings accurately and the process of doing so can be costly and time-consuming. This paper evaluates the energy use of a multi-zone VAV system with terminal reheat using the G36 sequences and compares it to a group of baseline control sequences that represent existing practices. Spawn of EnergyPlus is used for the whole building simulation, where the envelope is modelled in EnergyPlus and the HVAC equipment and its pressure-flow network and the control sequences are modelled in Modelica. The comparison of the control sequences performance is further conducted in parametric studies. For a medium-sized commercial building, the G36 sequences provide a wide range of HVAC energy savings with an average of 31%.

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KEYWORDS
ASHRAE Guideline 36; HVAC; control sequences; Modelica; EnergyPlus; energy efficiency

1. Introduction

To reduce the energy use of existing commercial buildings, retrofit efforts commonly focus on replacement or upgrades of building envelope, lighting or Heating, Ventilation and Air Conditioning (HVAC) systems (Ma et al. 2012). Due to their high capital costs, implementation complexities or varied effectiveness depending on climates, building types and sizes, or local utility rates, these conventional retrofit practices do not easily scale up (Chidiac et al. 2011; Regnier et al. 2018; Hong et al. 2015). On the other hand, low energy performance of existing buildings is often related to poorly designed or configured control systems, suggesting that better controls of energy systems could result in improvements of building performance and utility (Treado and Chen 2013; Barwig et al. 2002).

1.1. Related works

Applying better control design or control retrofit measures to HVAC systems were reported with large energy savings potential (Hydeman et al. 2003; Pang, Piette, and Zhou 2017; Fernandez et al. 2015, 2017; Cho and Liu 2010). A design guideline (Hydeman et al. 2003) for Variable Air Volume (VAV) airside system recommended a list of best practices for better controller design, where the 'best practice' controller was shown to save 25% annual HVAC energy on average against 'standard practice'. Pang, Piette, and Zhou (2017) studied how variations of the VAV system controls impacted HVAC energy performance and reported that, using different control strategies, the HVAC energy use could vary by up to 63.9% and 66.5% for Chicago, IL and Houston, TX respectively. There were six primary control strategies investigated: Supply Air Temperature (SAT) reset, Duct Static Pressure (DSP) reset, zone minimum airflow control, economizer control, minimum outdoor air intake and optimal start. Different values of occupied and unoccupied setpoints for room heating and cooling were also investigated. The DSP reset logic was, however, not explicitly modelled in the work nor were actuating devices (e.g. dampers or valves) due to the limitation of EnergyPlus modelling capabilities.

A large number of 're-tuning' measures were studied for both airside and water-side HVAC systems in large

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office buildings across 16 U.S. climates using EnergyPlus (Fernandez et al. 2015). Both individual measures and combinations of measures were simulated, where some combinations of measures yielded up to 75% annual energy savings. A companion report from the same team included more results for nine prototype buildings using the same methodology (Fernandez et al. 2017). Simulation results showed that, with better HVAC controls, the potential national total site energy savings ranged from 23% to 30% for most building types, with the exception of standalone retail reaching 41% and secondary school reaching 49%. For the medium office building, the same building archetype studied in this paper, the report showed that in average, the minimum airflow control saved 16.1%, SAT reset 6.6% and DSP reset 3.6% of building site energy across different climates. Assuming the savings from different control strategies were accumulative, the three strategies in that report all together saved 26.3%. Authors in Cho and Liu (2010) implemented improved control sequences of the VAV systems through Continuous Commissioning (CC) on a real five-story office building. Measurements and operation analysis showed 27% of electricity savings and 48% of gas savings compared with pre-commissioned control sequences. Another study (Zhou, Haberl, and Cheng 2017) implemented DSP reset control strategy in five governmental buildings. Demonstration results showed that the fan energy savings in any particular one AHU ranged from 1.5% to 52.9% compared with fixed static pressure control.

In 2018, the American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) published the Guideline 36 (G36) *High-Performance Sequences of Operation for HVAC Systems* (American Society of Heating, Refrigeration and Air conditioning Engineers 2018) upon completion of the Research Project 1455 (Hydeman, Taylor, and Eubanks 2015). G36 provides a set of best-in-class control sequences to reduce programming, commissioning and engineering time with improved performance in energy efficiency and indoor air quality. The initial version of G36 has included sequences of operation (SOO) for airside VAV systems and terminal units. The development of additional control sequences is underway for waterside equipment and systems through ASHRAE Research Project 1711 (Taylor 2018; Taylor, Gill, and Kiriu 2020), as of writing this article.

To effectively scale the installation of G36 control sequences in retrofit applications or controls upgrade projects, barriers exist for building owners and operators. For example, for control retrofits, considerable expertise and custom programming may be required for the specific project (Treado and Chen 2013). The energy savings potential of G36, therefore, needs to justify the costs of determining the opportunity for retrofit as well as the implementation of the retrofit. However, as of writing this paper, research related to the G36 control sequences is still rare. In Abdel Haleem, Pavlak, and Bahnfleth (2020), the effects of uncertainty in HVAC systems with G36 control sequences were investigated. Based on Monte Carlo analysis, the impact of uncertainty on G36 sequences performance were evaluated in terms of thermal comfort, indoor air quality (IAQ) and energy use. One interesting finding was that measurement errors of supply air and zone air temperatures introduced by temperature sensors produced the greatest degradation of the G36 control system performance. Authors in Ferretti et al. (2019) commissioned a subset of the G36 control sequences through functional performance tests using an HVAC-Cx commissioning tool, where test scripts were designed to assess compliance with G36 for multiple-zone VAV Air Handling Units (AHUs). Pritoni et al. (2020) developed a performance validation tool for G36 so that the implementation of the G36 sequences from different manufacturers could be evaluated for conformance with the Guideline. Wetter et al. (2018, 2021, 2022) implemented the G36 control sequences in the Control Description Language (CDL) (Wetter, Grahovac, and Hu 2018) and demonstrated the energy savings of G36 through a simulated case study on a five-zone office building model using Modelica (Mattsson and Elmqvist 1997; Modelica Association 2017). The estimated energy savings was approximately 34% for the Chicago climate. Authors in Kiriu and Stein (2021) implemented a large set of G36 sequences for the VAV systems in a medical office building along with upgrades of the existing BAS and pneumatic to DDC control. The achieved annual energy savings were 38.5% for the chilled water cooling system and 56% for the hot water heating system. The authors highlight that detailed commissioning was critical to ensure that the G36 sequences were programmed correctly and the system performed as intended. While these preliminary studies on G36 and specific control measures that are included in G36 show savings potential, further investigation of G36 sequences is needed against different baseline control sequences for a wider range of conditions, including different building types, climates and internal loads.

Buildings and HVAC systems have been studied substantially in simulations for energy conservation measures in the past decades (De Boeck et al. 2015; Ruparathna, Hewage, and Sadiq 2016). Yet, HVAC control sequences have not been explicitly modelled and investigated at-large in simulation studies due to limitations in conventional building energy modelling tools, e.g. DOE-2, EnergyPlus and ESP-r (Winkelmann et al. 1993; Crawley et al. 2001; Clarke 2001), which often implement greatly simplified control sequences for HVAC systems (Wetter 2009). The development of Spawn of EnergyPlus (Spawn) (Wetter et al. 2020) addresses this issue by combining EnergyPlus modules for building envelope, lighting and equipment modelling with HVAC and controls modelling in Modelica, providing end users the flexibility of envelope modelling from EnergyPlus with the capabilities of HVAC physical system and controls modelling in Modelica. The open-source Modelica Buildings Library (MBL) (Wetter et al. 2014) provides a foundation of physical equipment, system and control component models for Spawn. Furthermore, the OpenBuildingControl development effort (Wetter et al. 2018, 2021) developed the Control Description Language (CDL) (Wetter, Grahovac, and Hu 2018) for explicit representation of control sequences and a subsequent library of control sequences, which are included in the MBL and can be used for simulation with Spawn.

1.2. Objective and contributions

This paper evaluates the energy savings potential of retrofitting existing control sequences to the G36 control based on simulation studies for a multi-zone VAV system with single-duct terminal reheat. A group of baseline control sequences are developed to represent a range of existing practices for comparison with G36. To create the range of baseline control conditions, three specific control strategies are varied: Duct Static Pressure (DSP) reset, Supply Air Temperature (SAT) reset, and zone airflow control. These three control strategies are selected based on findings in Hydeman et al. (2003) and Katipamula and Fernandez (2020), which showed that these three control strategies were among the largest potential for energy savings in HVAC control retrofitting measures. Performance differences are also evaluated over three climates, three scenarios of building operating hours and three scenarios of internal load densities.

The paper is structured as follows. Section 2 details the simulation approach, where explicit control sequences, HVAC system and building envelope are modelled in Spawn. Section 3 presents the major modelling assumptions including modelling of the building envelope, HVAC system, stochastic occupancy and internal heat gains. Section 4 details the differences between the baseline and G36 control sequences. The parametric variables not representing control strategies are presented in Section 5. Results analysis and conclusions are found in the last two sections. The specific contributions of the paper include the following:

- The current work is an extensive study of the energy savings potential of G36 control sequences for the most common system configuration: a multi-zone VAV system with reheat terminals. It includes operations within three California climates, under a number of internal load conditions, and compared to various baseline control sequences.
- It is the first application of Spawn to evaluate control performance over a large range of conditions.
- The models in this study combine advanced, integrated modelling techniques including more realistic building zoning than the conventional five-zone, core-perimeter approach, a pressure-flow HVAC network model, explicit control sequences and stochastic occupancy schedules.

2. Approach

2.1. Simulation framework

In order to evaluate the energy savings of G36 control sequences, a key component of development in this work is the simulation framework. It needs to address two challenges: First, it needs to be computationally capable of simulating both conventional and G36 control sequences; and second, it needs to be flexible enough to accommodate large parametric variations of these sequences and building operating conditions.

The first challenge is rooted in the need for the coupled simulation of the pressure-flow relationship in VAV distribution systems, the HVAC equipment and the control sequences. The importance of modelling pressure-flow networks comes from the relationship between terminal unit damper position and supply fan speed control. This is central to the VAV system operation and critical to energy savings associated with control strategies such as duct static pressure reset. The importance of modelling explicit control logic comes from the desire to model the control sequences as they are written, and to limit the simplifications needed on the basis of modelling, and ultimately reduce the ambiguity on the source of savings. Conventional simulation tools such as EnergyPlus, however, present limitations and drawbacks in modelling pressure-flow networks in HVAC systems and explicit control sequences, as discussed in Section 1.1.

The second challenge is rooted in the need to adjust model parameters, climate, and occupancy and internal load schedules such that batches of simulations can be run in as automated a way as possible. Some variations are easier to implement than others. For instance, a new occupancy schedule with extended hours does not influence the design of the HVAC system and its control. Meanwhile, a new climate requires resizing the HVAC system and a new control strategy requires a new control model altogether.

With these challenges in mind, the simulation framework used in this study utilizes the state-of-the-art Spawn software. Spawn is the latest whole-building energy simulation engine developed by the U.S. Department of Energy, its National Labs, and industry for new use cases, including for the design and performance assessment of controls. Spawn is not a direct successor of, nor is intended as an imminent replacement for, EnergyPlus. Spawn reuses the envelope model of EnergyPlus, and couples it internally to HVAC system and control models from the MBL. While the development of Spawn also includes the development of numerical methods, template models and packaged software for end users, this paper uses the EnergyPlus-Modelica co-simulation coupling developed by the Spawn team, which is integrated in the MBL. Figure 1 gives an overview of how Spawn is used in this study. In this setup, because Spawn uses Modelica for the HVAC and control systems, it addresses the first challenge above. Furthermore, because it uses the EnergyPlus envelope model, it also addresses the second challenge above, particularly for system resizing through the legacy EnergyPlus HVAC system sizing capability, and also for zone definition and configuration through EnergyPlus input data files (.idf). The stochastic occupancy schedules are produced using the tool OccupancySimulator (Chen, Hong, and Luo 2018) and the internal gains are further created based on the generated stochastic occupancy schedules. The overall building operation schedule, output from the OccupancySimulator, is used for zone temperature setpoint reset and HVAC operations each day.

At the start of the simulation, Spawn automatically creates a Functional Mockup Unit (FMU) of the EnergyPlus envelope model and imports the FMU into the Modelica model, where it is linked to an FMU containing the Modelica HVAC system and control models. The Modelica simulation environment also incorporates a weather file containing Typical Meteorological Year (TMY) data from a chosen location (a .mos file, akin to 'EnergyPlus Weather (EPW)' files) and .csv files that define occupancy, lighting, and equipment schedules for every hour of the year. Note that the .mos and .epw files contain the same weather data but in different formats.

In Modelica, the HVAC system and controls are modelled using components from the MBL. The G36 control sequences have already been implemented in the MBL in CDL as part of the OpenBuildingControl project. As described in Section 1.1, CDL is a subset of the Modelica modelling language that can be used to specify control sequences in computer code such that they 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. For these sequences, default values of the parameters (e.g. timestep and trim and respond amounts in the G36 *Trim & Respond* logic) in the MBL have been used except for those related to building design and occupancy, such as number of zones, area of each zone, and design occupant density of each zone, as well as the minimum and maximum limits applied to static pressure reset, which are set to match those of the conventional pressure reset strategy described in a later section. For this work, the building is assumed to have no occupancy or CO_2 sensors, but the implemented G36 logic does allow for these cases.

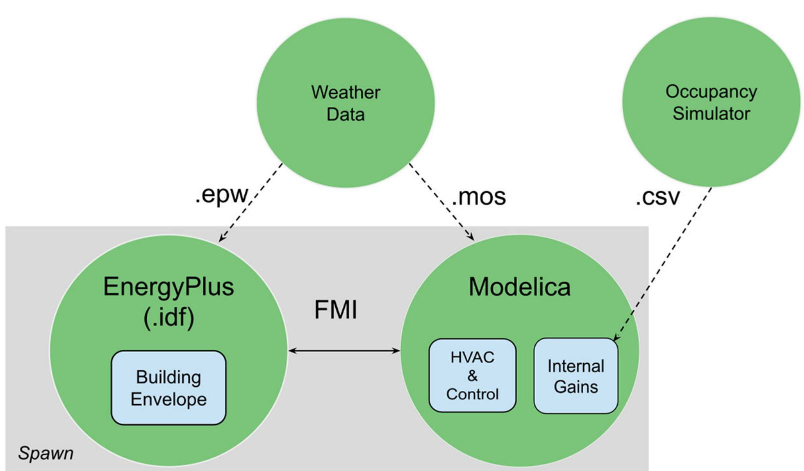

Figure 1. Simulation framework using Spawn, in which the building envelope is modelled in EnergyPlus, and the HVAC and control systems are modelled in Modelica. EnergyPlus and Modelica exchange data in the format specified by the Functional Mockup Interface (FMI) standard. Internal gains are also modelled in Modelica, informed by occupancy schedules developed by the OccupancySimulator tool.

The conventional control logic for terminal units has already been implemented in the MBL, while the conventional control strategies for the economizer, static pressure reset, and supply air temperature reset described in Section 4 were implemented as part of this research. The minimum and maximum supply air temperature reset limits match those defaults from the G36 sequence implementation.

2.2. Simulation workflow

Three primary software tool environments are used in the simulation framework: EnergyPlus, OccupancySimulator, and Dymola. EnergyPlus is used in two procedures: it is used as a part of Spawn for simulating control performance, and prior to that, it is invoked to size the HVAC system using its auto-sizing functionality. Note that during the auto-sizing procedure, the assumption of internal heat gains and occupancy stays at the design condition, as opposed to any of the parametric variations described in Section 5. Figure 2 presents a brief summary of the simulation workflow.

The OccupancySimulator tool is used to generate stochastic occupancy schedules offline. These schedules set the internal gains due to people, lighting, and equipment in occupied zones, as well as HVAC system operation schedule. For zones without occupants, a deterministic schedule for lighting and equipment is used. The data for internal loads are then imported through .csv files in Modelica and sent to the EnergyPlus FMU during simulations. Details about the assumptions of the internal gains can be found in Section 3.4.

Dymola 2021 was used as the Modelica development environment. For the parametric simulation runs, BuildingsPy (Wetter 2020) is used to change parameters in the Modelica model before each run. Then, Dymola 2021 is used to translate and simulate the Modelica model. Radau is used as the solver with a tolerance of 1E−06. The simulated outputs in .mat format are processed into .csv files using BuildingsPy for further analysis and visualization in Python (Van Rossum and Drake 2009).

3. Modelling of building envelope and HVAC system

3.1. Building envelope and zoning

The building envelope model starts from the updated OpenStudio medium office prototype models (Im, New, and Bae 2019), which are adapted from the DOE commercial reference building benchmarks models (Deru et al. 2011) to be more representative of the zoning variety of a typical office building. The floor model has 21 zones composed of 10 zone types that are arranged as shown in Figure 3: open office, closed office, corridor, storage, conference room, stairway, lobby, restroom, equipment room and dining room. The construction properties are from the ASHRAE Standard 90.1-2004 (American Society of Heating, Refrigeration and Air conditioning Engineers 2004) with specifications dependent on climate zones. Each climate zone therefore has one EnergyPlus input file (.idf) for the building envelope model and one weather data file (.epw). The envelope infiltration model uses the Design Flow Rate model in EnergyPlus for the

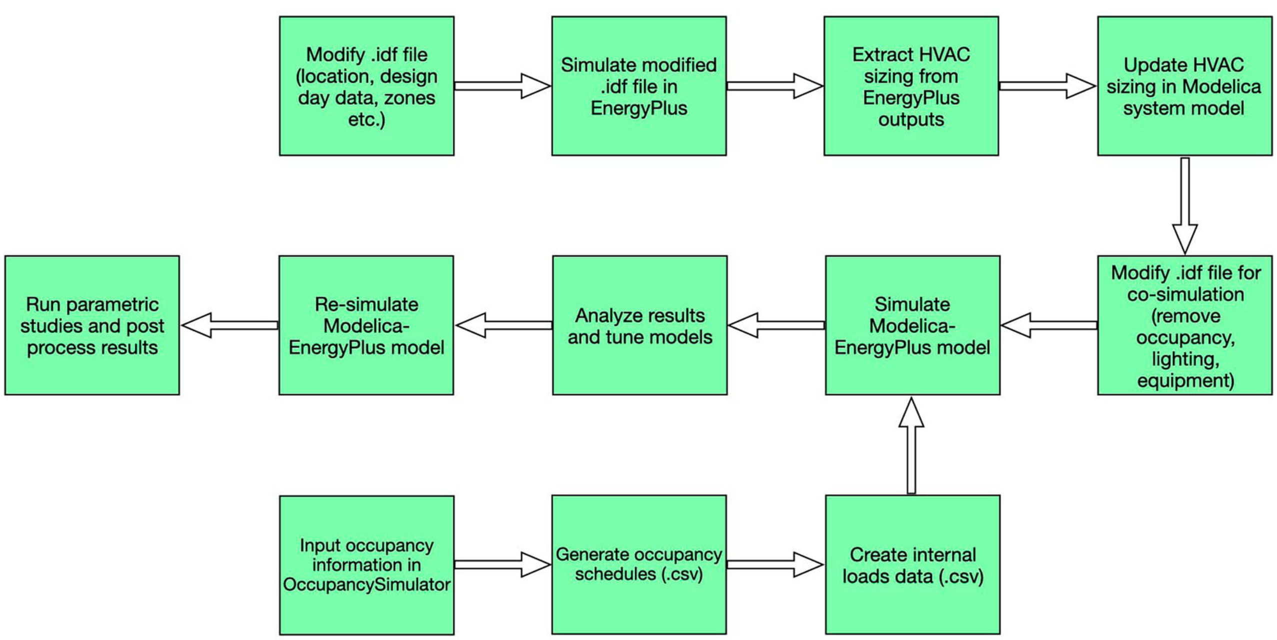

Figure 2. Simulation workflow.

system sizing calculations, where the flowrate input of about 0.001 $m^3/(s{\cdot}m^2)$ is assumed per exterior surface area. The infiltration is, however, not modelled in the co-simulation using Spawn. Note that the inter-zone air exchange is not modelled.

The building structure is adapted from the original EnergyPlus models by considering only the middle floor with a floor area of 1662 m^2 and 33% window-to-wall ratio equally distributed on each facade. This adaptation is to make the building floor more generic, representing a single floor in a mid- or high-rise building. The envelope consists of four walls, a floor, and a ceiling. Thermal mass of the floor and ceiling is considered with adiabatic boundary conditions on the exterior surfaces.

3.2. HVAC system

The VAV system is modelled as a detailed single-duct pressure-flow network, which comprises an air handling unit (AHU) with a supply fan, an economizer, a hot water heating coil, and a chilled water cooling coil, and 21 pressure-independent VAV boxes with dampers and hot water reheat valves. The graphic representation of the AHU and VAV box in Modelica is shown in Figures 4 and 5. Table 5 in Section 8 lists the main model components used in this study from the MBL. The heating and cooling plants are not modelled explicitly. Instead, hot and chilled water are assumed to be produced from ideal water sources at constant temperatures of 45°C for hot water and 6°C for chilled water. Constant coefficients of performance are used to convert heating or cooling provided to electrical power consumption, with $COP_h = 4.0$ for heating and $COP_c = 3.2$ for cooling.

The HVAC system is sized using the EnergyPlus autosizing function. In the sizing simulation, the internal loads remain at the design load as described in Section 3.4. This means that the sizes of the HVAC system are the same for all parametric variations within a given climate. For each climate, an annual simulation is first run using the corresponding EnergyPlus model to obtain the nominal system airflow rate for the AHU system and the nominal zone airflow rate for each zone. The supply fan, heating coil, cooling coil, and reheat coils are then sized based on those nominal airflow rates in the HVAC system model. The sizing approach for the coils is adopted from the MBL component models `Buildings.Examples.VAVReheat.BaseClasses.PartialOpenLoop` for AHU coils and `Buildings.Examples.VAVReheat.ThermalZones.VAVBranch` for terminal unit coils and detailed below. The sizing equations ensure that there is enough water flowrate to meet the load. They also compute the nominal characteristics of the coil models, such as the nominal *UA* value. The parameter values in the equations below are from the default values in the MBL.

The nominal heating power $\dot{Q}_{hea,AHU,0}$ of the heating coil in the AHU is

$$\dot{Q}_{hea,AHU,0} = \dot{m}_{sys,0}\, c_{p,air}\, (T_{air,lea,0} - T_{air,ent,0}), \qquad (1)$$

where $\dot{m}_{sys,0}$ is the system nominal air mass flowrate, $c_{p,air}$ is the specific heat capacity of the air, $T_{air,lea,0} = 16.7°C$ is the leaving air temperature at nominal conditions, and $T_{air,ent,0} = 8.5°C$ is the coil entering air temperature at nominal conditions. Note that the heating cool is primarily used for freeze protection.

The nominal mass flowrate of water $\dot{m}_{hea,AHU,0}$ of the heating coil in the AHU system is sized as

$$\dot{m}_{hea,AHU,0} = \frac{\dot{m}_{sys,0}\, c_{p,air}\, (T_{air,lea,des} - T_{air,ent,des})}{c_{p,wat}\, \Delta T_{wat}}, \qquad (2)$$

where $T_{air,lea,des} = 10°C$ is the design leaving air temperature of the heating coil, $T_{air,ent,des} = -20°C$ is the design entering air temperature, $c_{p,wat}$ is the specific heat capacity of water and $\Delta T_{wat} = 10°C$ is the expected change in water temperature across the heating coil.

The nominal heating power $\dot{Q}_{reh,0}$ of the reheat coil in each zone is

$$\dot{Q}_{reh,0} = \dot{m}_{zon,0}\, c_{p,air}\, (T_{air,dis,0} - T_{air,lea,0}), \qquad (3)$$

where $\dot{m}_{zon,0}$ denotes the nominal air mass flowrate to each zone, $T_{air,dis,0} = 50°C$ is the nominal condition discharge air temperature.

The nominal mass flowrate of water $\dot{m}_{reh,0}$ of the reheat coil in each zone is sized using

$$\dot{m}_{reh} = \frac{\dot{m}_{zon,0}\, c_{p,air}\, (T_{air,dis,0} - T_{air,sup,0})}{c_{p,wat}\, \Delta T_{wat}}. \qquad (4)$$

The cooling coil model is a wet coil model. Its nominal UA value UA_0 value is calculated for design temperatures of $T_{air,ent,coo} = 26.2°C$, $T_{air,lea,coo} = 12.8°C$, $T_{wat,ent,coo} = 6°C$, and $T_{wat,lea,coo} = 16°C$.

The HVAC system is simulated with a supply fan only and no return fan. The return fan is not modelled for simplicity and because the low associated energy use would not be expected to appreciably impact the final result. The nominal AHU pressure drop is assumed to be 540 Pa, duct and terminal unit pressure drop for each zone branch in parallel is assumed to be 240 Pa, and return duct pressure drop is assumed to be 40 Pa. The hydraulic and motor efficiencies of the fan are assumed to be a constant 0.7 each.

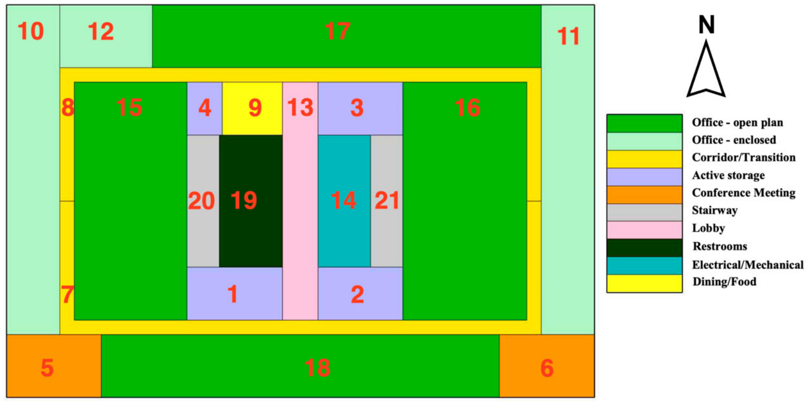

Figure 3. The building floor model consists of 21 zones and 10 zone types (Im, New, and Bae 2019).

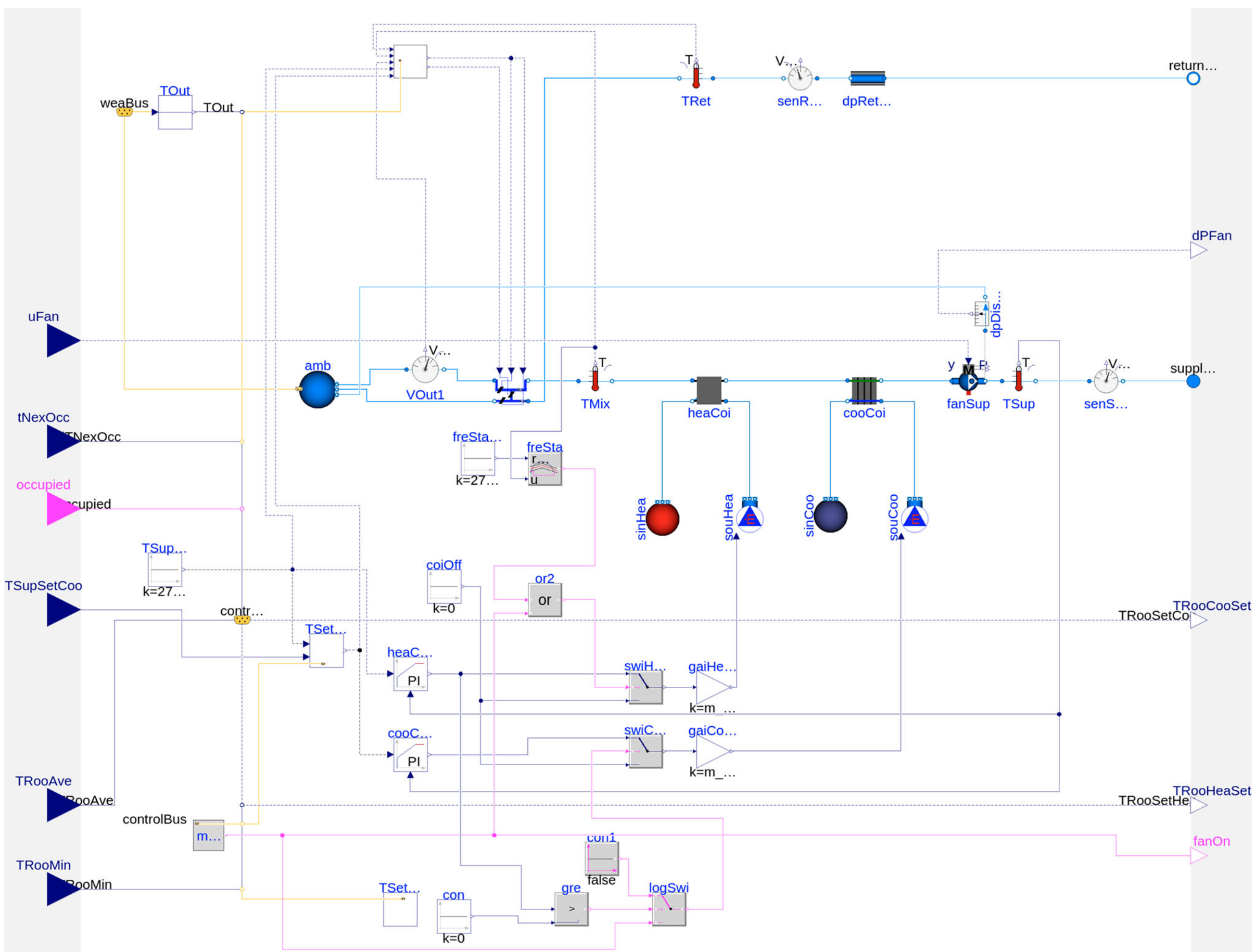

Figure 4. High-level AHU and its control system implemented in Modelica.

3.3. Occupancy

Among the 21 zones, 13 zones have occupancy during operation hours, while the eight remaining zones are considered to never be occupied. The eight zones considered always unoccupied are the four storage rooms, two stairways, one equipment room and one restroom. The occupancy schedules for each of the remaining 13 zones with occupancy are stochastic profiles obtained by using the OccupancySimulator tool. The tool takes as inputs the space types and areas, design occupant density and types (e.g. regular staff, manager, etc.), and events in the spaces (e.g. short-term leaving). Then, it simulates the occupants'

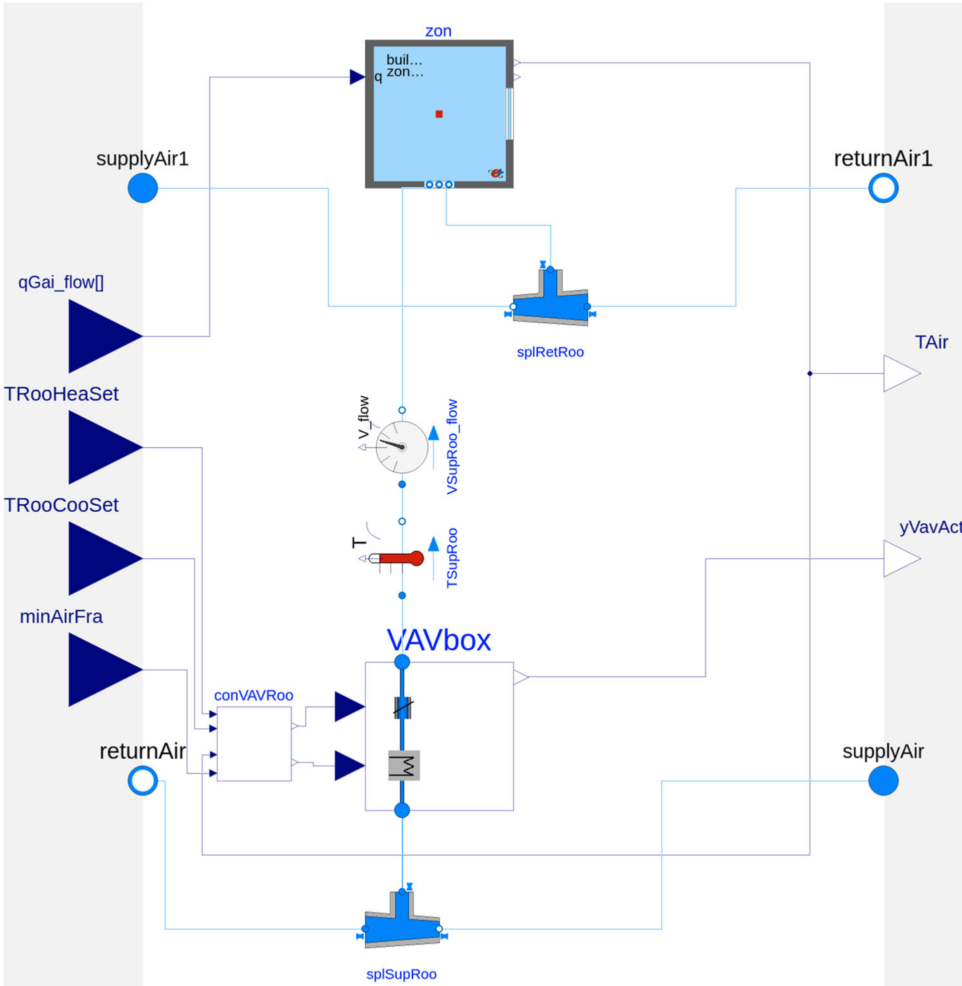

Figure 5. Zone-level system and VAV box control implemented in Modelica.

movement from one space to another based on a Markov-chain model. In the end, a schedule of the number of occupants at every hour of the year is produced for each zone.

In the OccupancySimulator, a design occupant density is only given for the open and closed offices. They are assumed to be 20 m^2/person for the open offices and 18 m^2/person for the closed offices per ASHRAE 90.1-2004. Default values for occupant types, percentage of occupants, and events in each category of rooms from the tool are used. The arriving and leaving time for each occupancy type are consistent with the building operation time as described in Section 5.2. Finally, using all of this information, the number of occupants at each hour of the year in the open and closed offices, as well as the two meeting rooms, one lobby, two corridors, and one dining room, are calculated by the OccupancySimulator tool.

Figure 6 shows the number of occupants for zone 10 (closed office), zone 15 (open office), and zone 5 (meeting room) for three consecutive days. The locations of the three zones can be seen in Figure 3. Note that the occupancy scenario is the low operating hours scenario with 50 hours per week, as described in Section 5.2. The lower plot shows the total internal gains due to occupants for those three zones.

3.4. Lighting and equipment

Lighting and equipment schedules for each zone are based on the occupancy schedule of that particular zone. For zones without occupants, such as storage rooms, a deterministic schedule is assumed with opening and closing hours of the building. The same schedule applies to both lighting and equipment.

The assumption made for the lighting load is that when the zone is occupied (greater than 0 number of occupants for zones with occupants, or in operational hours for zones without occupants), it has 100% of the maximum lighting load. When the zone is unoccupied, it

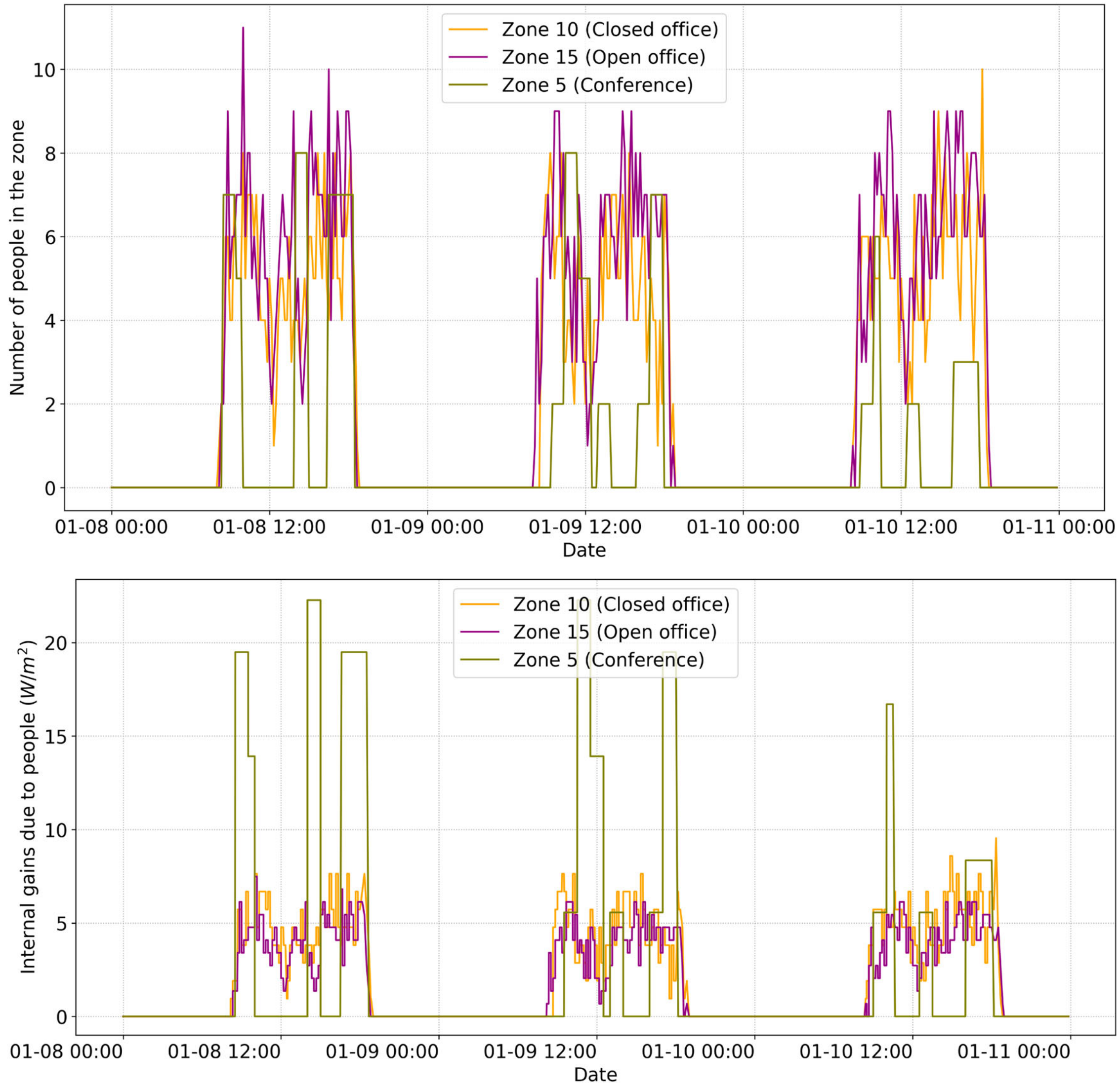

Figure 6. Number of occupants for selected zones (top) and total internal gains due to occupants for those zones (bottom).

Table 1. ASHRAE standard 90.1-2004 design maximum load for lighting and equipment.

Space type	Lighting (W/m^2)	Equipment (W/m^2)
Storage	8.6	0
Stair	6.5	0
Restroom	9.7	2.9
OpenOffice	11.8	10.3
Lobby	14.0	2.9
Elec/MechRoom	16.1	2.9
Corridor	5.4	3.1
Conference	14.0	10.8
ClosedOffice	11.8	9.4
Dining	9.7	10.8

has only 5% of the maximum lighting load. The design maximum load values for each zone type are from the ASHRAE Standard 90.1-2004 as shown in the first column of Table 1. Figure 7 presents the total internal gains resulting from the design maximum values for lighting for the same zones and times as shown in Figure 6.

The equipment schedules for each zone are assumed to be the same as the occupancy schedule of the corresponding individual zone when the zone is occupied, in terms of percentage of maximum load. The zone has 10% of the maximum equipment load when the zone is unoccupied. For zones without occupants, the occupied period corresponds to operational hours and unoccupied otherwise. The design maximum load values based on ASHRAE 90.1-2004 for each zone type are shown in the second column of Table 1. Figure 8 presents the internal gains resulting from the design maximum values for equipment for the same zones and times as shown in Figures 6 and 7.

4. Control system

To evaluate the energy savings potential due to the G36 control sequences, a set of conventional controls

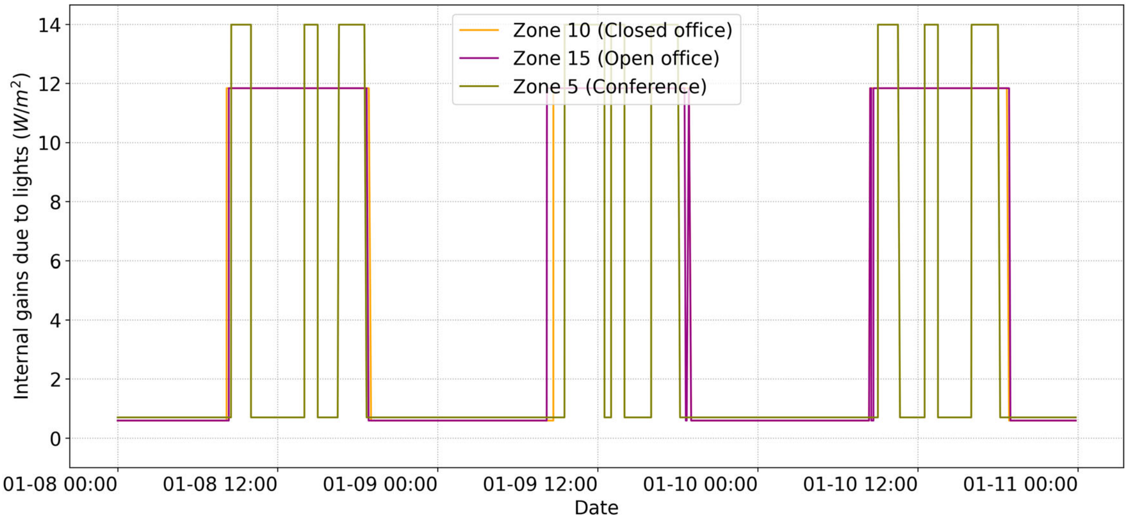

Figure 7. Total internal gains due to lighting for selected zones.

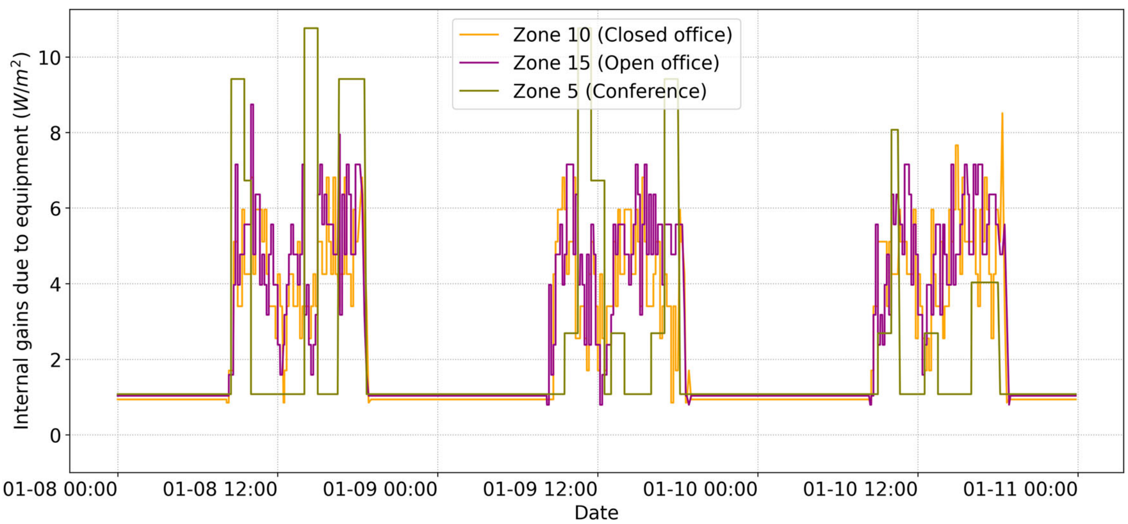

Figure 8. Total internal gains due to equipment for selected zones.

have been created as baselines for comparison. Both the baseline and G36 control sequences are applied to the same building and HVAC system models as described in Section 3 to compare the resulting energy consumption differences. The conventional control sequences adopted in this work were originally based on the descriptions in the ASHARE 2006 Guideline *Sequences of Operation for Common HVAC Systems* (American Society of Heating, Refrigeration and Air conditioning Engineers 2005). This Section discusses the differences of the conventional and G36 control sequences in the simulations, as well as the different assumptions made for the set of baseline controls which aim to represent a range of potential control implementation scenarios in existing buildings.

As mentioned in Section 1.2, three prominent control strategies are varied to create the range of conventional baselines: duct static pressure reset, supply air temperature reset, and zone airflow control. Three levels of configurations for each control strategy were determined: Base, Mid and G36. Table 2 shows a summary of the control strategies at each level. The G36 scenario represents the control sequences from the Guideline 36, while both the Base and Mid scenarios represent conventional control strategies found in practice. The parameter values in the Table are based on our experience from VAV system implementations in real buildings.

4.1. Duct static pressure reset

As shown in the second column of Table 2, for the DSP reset, the Base scenario assumes a constant pressure of 410 Pa. The Mid scenario varies the pressure between 50 Pa and 410 Pa based on PI feedback control from the zone with the most open damper. Specifically, a PI

Table 2. Control strategies of the three principle control configurations.

Control strategy	Base	Mid	G36
Duct static pressure	Constant 410 Pa	Limiting zone [50, 410] Pa	Trim and Respond [50, 410] Pa
Supply air temperature	Constant 12°C	Linear [12, 18]°C	Trim and Respond [12, 18]°C
Zone airflow	Single maximum $V_{min} = 30\%V_{max}$	Single maximum $V_{min} = 20\%V_{max}$	Dual maximum $V_{min} = \max(15\% V_{max}, V_{min\,OA})$

controller adjusts the static pressure setpoint to maintain the maximum damper position of all zones to a set point of 90% open. The G36 scenario uses the *trim and respond (T&R)* strategy based on the number of requests from the zones. In general, the *T&R* strategy resets a setpoint of an HVAC system (e.g. static pressure) by reducing the setpoint value at a fixed rate until sufficient requests of setpoint increase are present. In response, the strategy increases the setpoint until the requests are below the sufficient number. Afterwards, the strategy then resumes decreasing the setpoint and the process iterates. Taylor (2015) states that the *T&R* strategy is more effective in several aspects than PID control.

4.2. Supply air temperature reset

The SAT reset strategy in the Base scenario sets the SAT setpoint to a constant value of 12°C, while the Mid scenario resets the SAT setpoint linearly as a function of the outdoor air temperature as follows: when the outdoor air temperature varies between 16°C and 21°C, the SAT setpoint varies linearly between 18°C to 12°C. The G36 scenario uses again the *T&R* strategy, which dynamically resets the SAT based on the number of requests from the zones. The upper and lower limits for the reset are the same for each case.

4.3. Zone airflow control

The Base and Mid zone airflow control scenarios use the strategy called single maximum VAV control logic as shown in Figure 9. In heating mode, the airflow remains constant at the minimum airflow with the reheat valve adjusting based on the need for heating. In cooling mode, the airflow modulates between the minimum and maximum value as a function of the need for cooling. The minimum airflow during deadband mode, V_{min} is the same as the heating airflow and is as listed in Table 2 as a percentage of the design airflow rate, V_{max}.The G36 control strategy for zone airflow control is called dual maximum VAV control sequences and is shown in Figure 10. In heating mode, the zone airflow is modulated between a minimum and maximum heating airflow and in cooling mode, zone airflow is modulated between a minimum and maximum cooling airflow. In the simulated cases, the minimum cooling airflow is set to be 15% of the maximum cooling airflow or the minimum zone outdoor airflow,

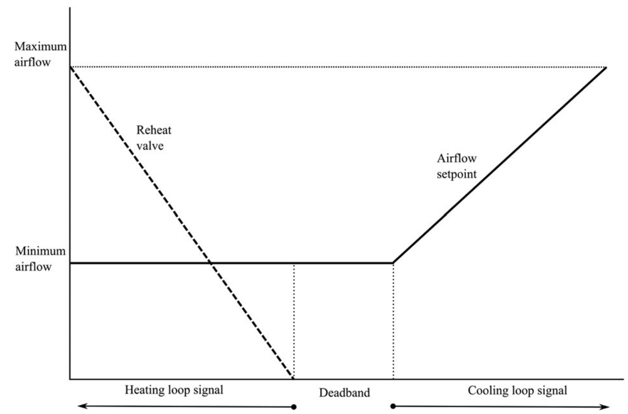

Figure 9. Baseline zone airflow control: Single maximum VAV control logic with reheat.

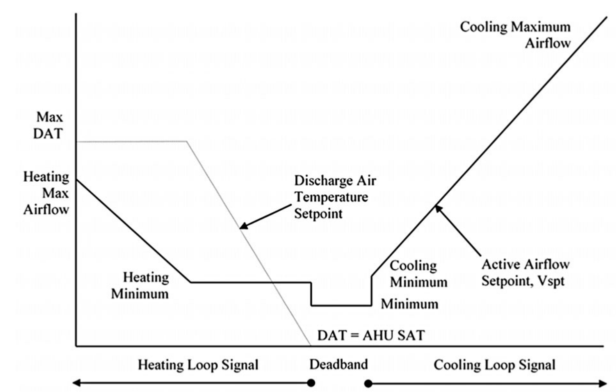

Figure 10. Guideline 36 zone airflow control: Dual maximum VAV control logic with reheat (American Society of Heating, Refrigeration and Air conditioning Engineers 2018).

$V_{min\,OA}$, if it is larger than the minimum cooling airflow. In heating mode, the minimum airflow is set to be the same as that in cooling mode, whereas the maximum heating airflow is set to be 50% of the cooling maximum.

To capture a range of baseline controls, we assume that the Base and Mid control strategies can be inter-mixed

Table 3. Nine control configurations due to different combinations of parametric variables.

	Base	Mid	G36
Duct static pressure (A)	A1	A2	
Supply air temperature (B)	B1	B2	
Zone airflow control (C)	C1	C2	
A1B1C1(Base), A1B1C2, A1B2C1, A1B2C2, A2B2C2(Mid), A2B1C1, A2B1C2, A2B2C1			

with each other, while retrofit will always implement the full G36 sequences. The G36 strategies are therefore not mixed with the Base and Mid scenarios. Table 3 shows the nine combinations of control strategies that were simulated: eight combinations of baseline cases, made up of mixes of Base and Mid strategies, and one G36 case. Besides the three control strategies discussed above, some other minor differences exist between the conventional and G36 control sequences as discussed below.

4.4. Economizer control

For the baseline control strategies, the economizer control implements the differential dry bulb strategy and is modelled based on `Buildings.Examples.VAVReheat.Controls.Economizer` in the MBL. For the G36 control, the differential dry bulb control strategy is used as defined in the G36. In the baseline controls, the economizer is enabled if the outside air dry bulb temperature is less than the return air dry bulb temperature, with a hysteresis of 0.1 K. When the economizer is enabled, the outside air damper is controlled to maintain the temperature of the mixed air at a mixed air temperature setpoint. In this model, this setpoint is equal to the cooling supply air temperature setpoint minus 1.67°C, a value based on field experience. The minimum allowed damper position is controlled to maintain the minimum required outside airflow during occupied hours, with an override for freeze protection.

4.5. Minimum outdoor airflow control

The minimum outdoor airflow is calculated according to the G36 requirements using ASHRAE Standard 62.1-2019 (American Society of Heating, Refrigeration and Air conditioning Engineers 2019). The first few steps to calculate the minimum outdoor airflow in the G36 are consistent with the ones from the Standard 62.1. They are as follows: First calculate the uncorrected outdoor air volume flowrate based on the area and number of occupants in each zone, which are then corrected using coefficients such as zone air distribution effectiveness, occupant diversity and system ventilation efficiency. For the calculation of system ventilation efficiency, G36 takes the alternative approach as prescribed in the ASHRAE 62.1 ventilation rate procedure instead of the simplified method. The final step in G36 indicates that the effective minimum outdoor airflow rate should be no larger than the design total outdoor airflow rate. To make the baseline and G36 cases comparable, the same system minimum outdoor airflow, as maintained by the G36 sequence, is applied to all cases. The VAV boxes in the baseline cases only control to the minimum zone airflow as defined in Table 2 while in G36 cases, the zone minimum airflow is set to be equal or larger than the individual zone minimum outdoor airflow. Please note that the minimum zone airflows are not dynamically reset in the G36 model.

4.6. Control of heating and cooling coils in the AHU

The control logic for the heating and cooling coils in the baseline controls is based on two different control loops. The heating loop is controlled to maintain a SAT of 10°C while the cooling loop is controlled to maintain a SAT of 12°C if there is no SAT reset. In G36, both coils are controlled in the same control loop based on a single SAT setpoint.

4.7. Operation modes

Another control difference between the baseline and G36 controls is the warm-up and cool down operation modes before the occupancy. The baseline controls always start the system 30 min prior to occupancy, while the G36 controller has a routine to check whether it is necessary to enter warm-up and cool down modes based on the indoor temperatures. When the indoor temperatures are within the deadband, then the G36 controller will determine that it is unnecessary to preheat or precool the building. Additionally, when the zone is unoccupied, the baseline controls do not have a setup mode, while G36 does. All examined control strategies use a setback mode.

5. Parametric variables

Three variables are selected to evaluate their impact on energy savings: climate, building operating hours, and density of internal loads in the building zones. The following sections describe these variables.

5.1. Climate

Sacramento, Los Angeles, and San Francisco are evaluated. The weather data not only provides different hourly values in the simulation, but is also used in a preprocessing step for determining the envelope properties and the nominal airflow rates, which were a result of the HVAC system sizing. The three weather locations fall into two ASHRAE climate zones: Sacramento and Los Angeles are in Zone 3B and San Francisco is in Zone 3C. Two types of building envelope properties based on ASHRAE 90.1-2004 corresponding to the climate zones are therefore considered in the model.

Table 4. Scenarios of operating hours.

Operation scenario	Weekdays	Saturdays	Sundays	Total hours per week
High	7:00–22:00	7:00–22:00	7:00–22:00	105
Medium	7:00–19:30	7:00–19:30	/	75
Low	8:00–18:00	/	/	50

5.2. Hours of operation

To assess the impact of the number of operating hours in the building, we considered three types of operating hours: high, medium and low, which are, respectively, 105, 75 and 50 hours per week. The detailed operation schedule of each scenario is shown in Table 5. Note that the OccupancySimulator tool is used to generate stochastic schedules for each scenario; the start time and end time of occupancy may randomly vary up to 30 minutes of the timetables in Table 4 based on the assumptions for all occupant types (e.g. regular staff, manager, etc.) defined in that tool.

5.3. Load density

Similar to the assessment of operating hours, three design load densities for lighting and equipment are included: high, medium and low. The high density is assumed to be the design load based on ASHRAE Standard 90.1-2004 as described in Table 1. Medium and low densities are assumed to be 60% and 30% of the high density, respectively.

6. Results and discussions

6.1. Overall results analysis

The combinations of the scenarios described in Section 5 result in 243 cases, of which 27 are G36 cases. Figure 11 presents a density plot of the total HVAC site energy use for all cases, where the 243 cases are sub-categorized into the nine control cases for the variations of climates, internal loads and operating hours. We can see that the G36 control strategy has the lowest minimum and maximum site HVAC energy use. Following G36, the Mid

Table 5. Main model components from the MBL used in this study.

Model name	Model name in the MBL
Heating coils	Buildings.Fluid.HeatExchangers.DryCoilEffectivenessNTU (with counterflow configuration)
Cooling coil	Buildings.Fluid.HeatExchangers.WetCoilCounterFlow
Supply fan	Buildings.Fluid.Movers.SpeedControlled_y
Economizer	Buildings.Examples.VAVReheat.BaseClasses.MixingBox
Zones	Buildings.ThermalZones.EnergyPlus.ThermalZone
Dampers	Buildings.Fluid.Actuators.Dampers.PressureIndependent
Temperature sensors	Buildings.Fluid.Sensors.TemperatureTwoPort
Flow sensors	Buildings.Fluid.Sensors.VolumeFlowRate
G36 AHU controller	Buildings.Controls.OBC.ASHRAE.G36_PR1.AHU.MultiZone.VAV.Controller
G36 VAV box controller	Buildings.Controls.OBC.ASHRAE.G36_PR1.TerminalUnits.Controller

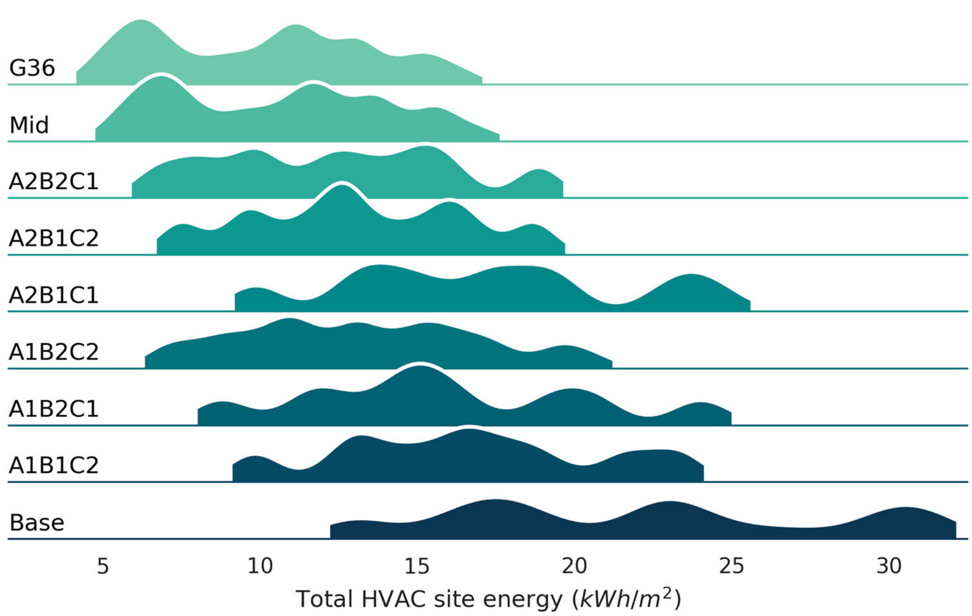

Figure 11. Density plot of total HVAC site energy for the nine control scenarios.

control strategy has the second-lowest minimum and maximum values, while the Base control strategy has the highest minimum and maximum values. The minimums and maximums of the mixed control strategies each lie between the Mid and the Base control cases. The distribution of G36 energy uses is relatively more concentrated, while the Base control strategy has a rather wide distribution of energy uses. The different distribution profiles of the energy use values suggest that the variations of climates, internal loads, and operating hours have more impact on the Base case than the G36 case.Comparing the eight baseline control strategy cases with G36 cases leads to 216 pairs of comparison with the same conditions of climate, internal loads, and operating hours. Among all of these 216 pairs, results show that the G36 control strategy presents a wide range of energy savings potential against each control strategy. The average energy savings of G36 is 31% and the median savings is 30% of all the comparisons. The maximum energy savings of G36 is 76% when compared with the Base control strategy for the San Francisco climate, low internal loads, and high operating hours scenario. The lowest energy savings occurs to be 2% when compared with the Mid control case for the Los Angeles climate, low internal loads, and high operating hours scenario.

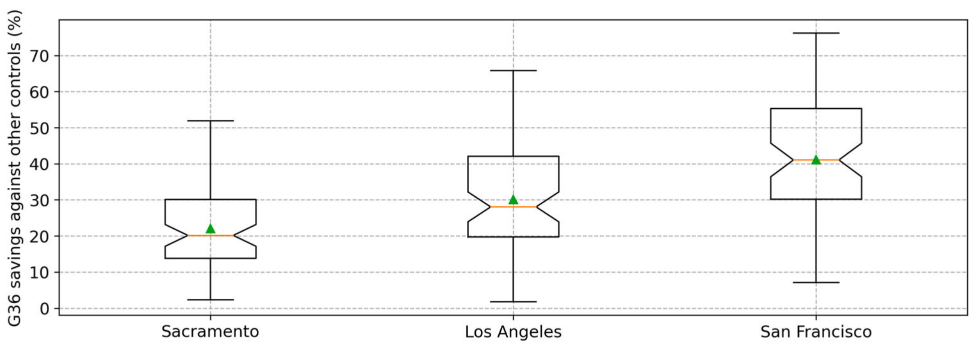

Figure 12. Impact of climate on energy savings of Guideline 36 against baseline controls under different operating hours and internal loads.

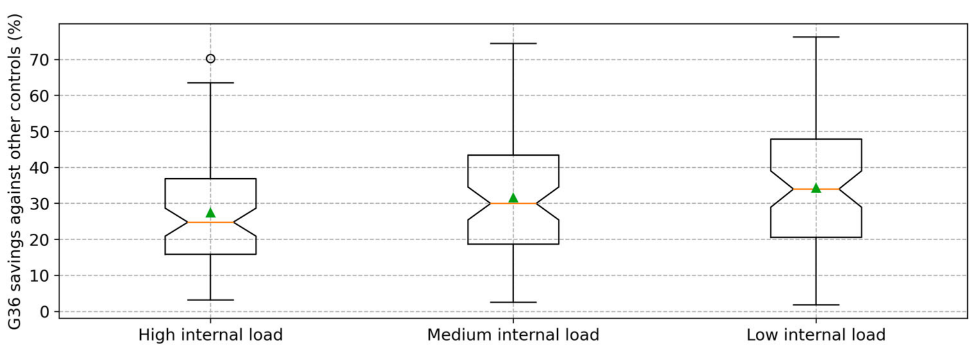

Figure 13. Impact of internal loads on energy savings of Guideline 36 against baseline controls under different climates and operating hours.

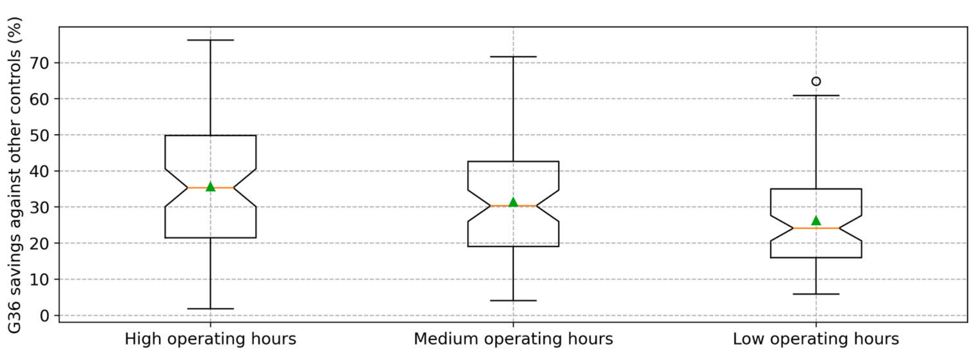

Figure 14. Impact of operating hours on energy savings of Guideline 36 against baseline controls under different climates and internal loads.

Figures 12, 13 and 14 show more detail about the impact of climate, internal loads, and operating hours on the energy savings of G36 against the other eight control strategy combinations. In the three boxplots, the orange lines indicate the median values of the energy savings while the green triangles indicate the average values of the savings. The boxes indicate values between the 25% and 75% percentiles. Note that statistically, there is no outlier case for the climate boxplot in Figure 12 and only one outlier case for each of the other two boxplots in Figures 13 and 14. Regarding the average and median energy savings, we see that the values are between 20%

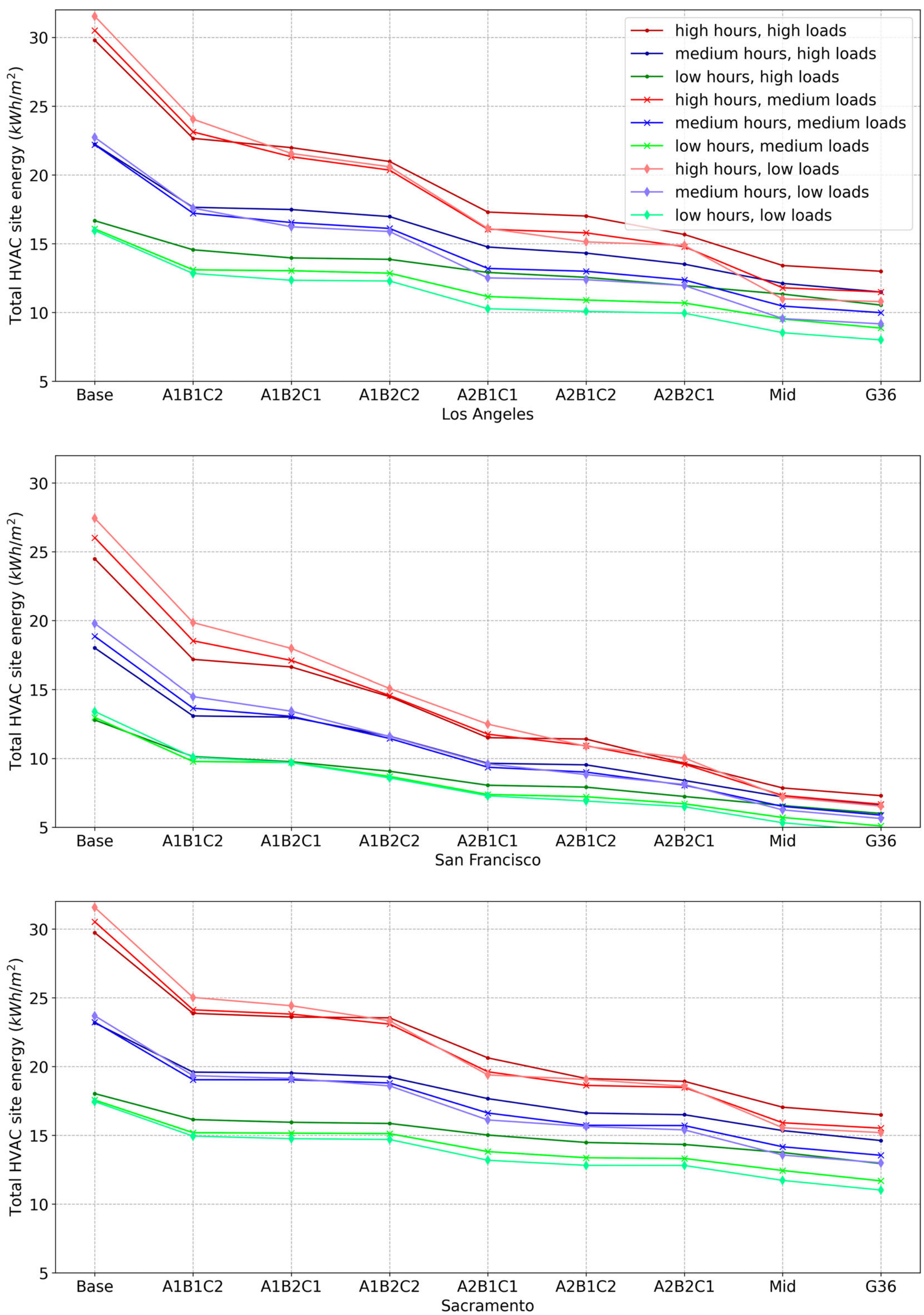

Figure 15. Impact of controls, operating hours and internal loads on HVAC site energy use for three climates.

and 40% across all three conditions. Together, Figures 12, 13 and 14 show that the highest savings potential occurs under conditions of the San Francisco climate, low internal loads and high operating hours. Meanwhile, the lowest savings potential occurs under the Los Angeles climate, low internal loads, and high operating hour cases. Comparing the three conditions, the climate has the most impact on energy savings, then operating hours and last the internal loads variations. As shown in Figure 11, the variations of those conditions have more influence on the energy use of the baseline cases, especially the Base and mixed control cases than the G36 cases. As a result, the energy savings of G36 become more varied against the baselines due to those variations.

A number of factors contribute to the energy savings of the G36 control. As can be seen in Figure 15, the conventional control strategy that is used as the baseline plays a significant role in the potential for savings. We can

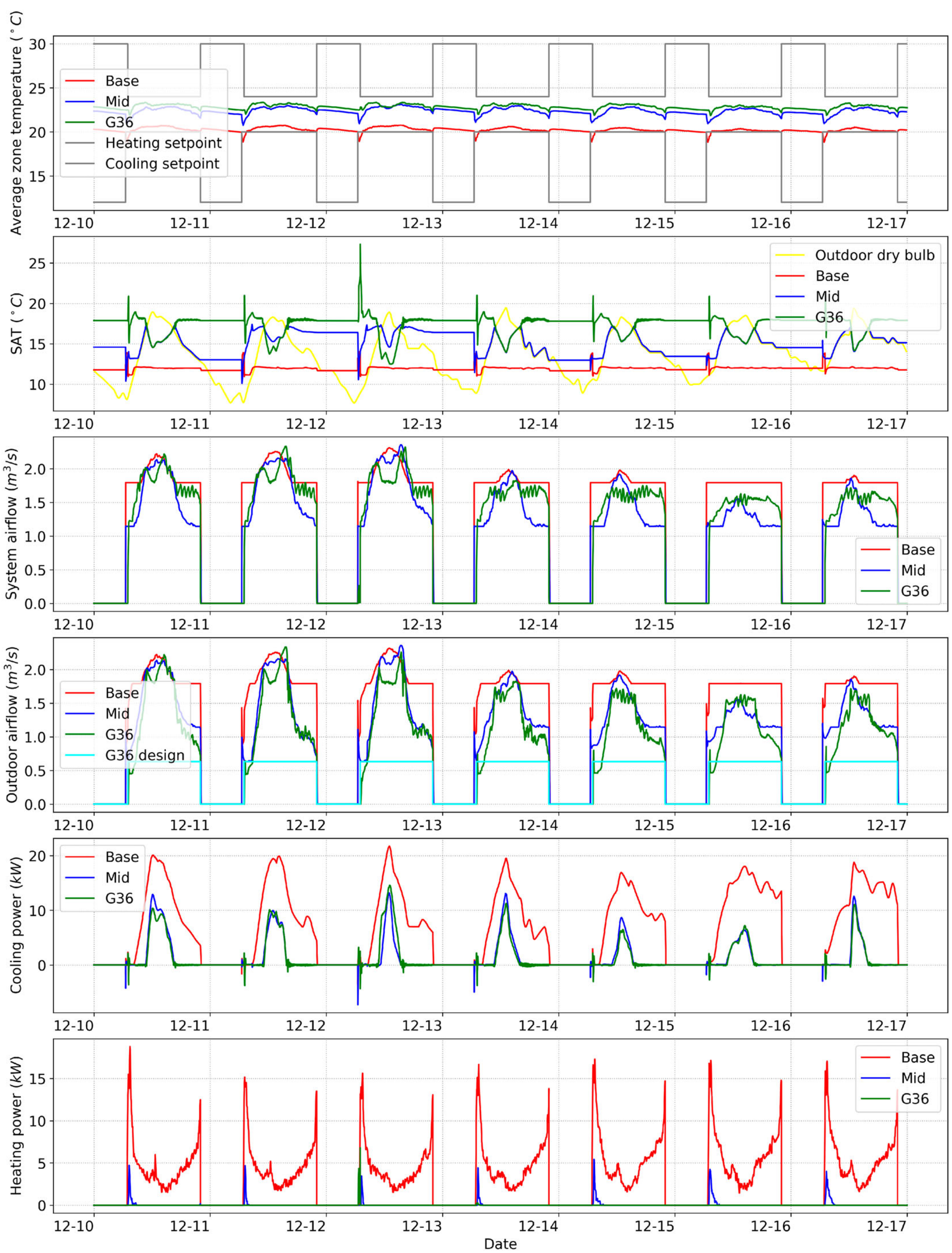

Figure 16. Profiles of the HVAC system operation for the three control cases (Base, Mid and G36) in a winter week in Los Angeles.

see that the energy use diminishes as the control strategies range from all Base controls, to different mixes of Base and Mid controls, to all Mid controls, and finally to G36 controls. In particular, implementing any one of the improved control measures reduces energy consumption compared to Base. In all three climates, the largest reductions in energy consumption from any singular strategy occur due to changes from A1 to A2 controls (DSP reset). This is particularly visible by comparing all the cases including A1 control (Base, A1B1C2, A1B2C1, A1B2C2) to all the cases including A2 control (A2B1C1, A2B1C2, A2B2C1, Mid). As the energy consumption decreases from Base to variations of Base and Mid to all Mid, so will the percent savings of G36 against a particular baseline case. Utilizing all Base control strategies shows to be very inefficient, due to both simultaneous heating and cooling in winter and shoulder seasons, due to lack of SAT reset, as well as increased fan energy because

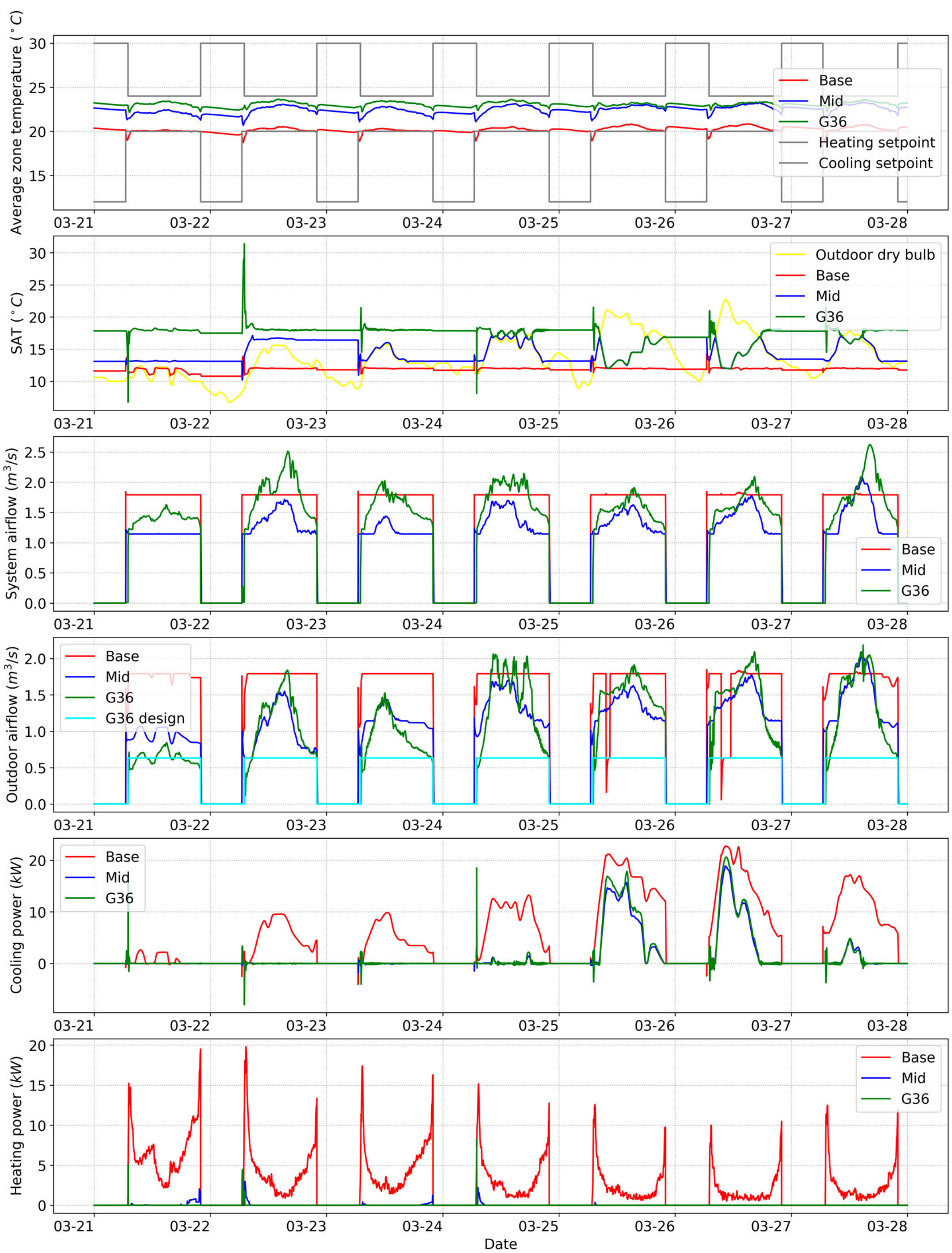

Figure 17. Profiles of the HVAC system operation for the three control cases (Base, Mid and G36) in a spring week in Los Angeles.

of no DSP reset. These reasons are detailed in the next Section 6.2. This leads to very significant savings potential from retrofitting to G36 in all climates and operating conditions. However, we expect that climate has the largest influence on energy savings in this study because the cooler climate of San Francisco offers large potential for saving on simultaneous heating and cooling and excess air flow. In addition, we expect that the number of operating hours has the next largest influence in this study due to the change in number of hours at part load, in the morning and in the evening and where there is greatest opportunity for savings, for each scenario.

6.2. Time series analysis

Figures 16, 17 and 18 show time series profiles in a winter, spring and summer week for the Los Angeles climate and three control strategies: Base, Mid and G36. The internal

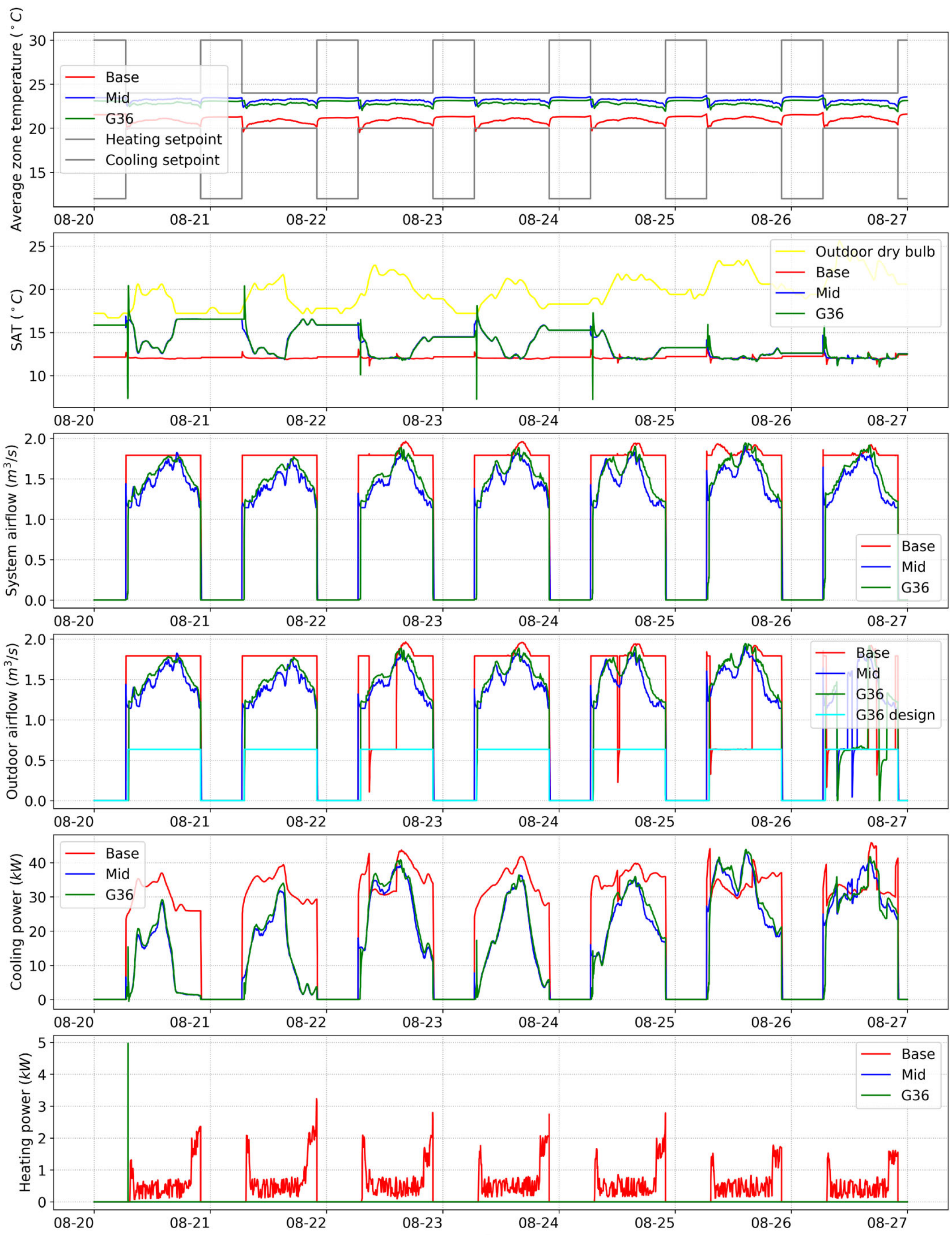

Figure 18. Profiles of the HVAC system operation for the three control cases (Base, Mid and G36) in a summer week in Los Angeles.

load is at the high scenario (100% of the design load) and the operating hours scenario is also at the high scenario (7 days a week). For each control method, the average zone air temperature is shown to be kept within the heating and cooling setpoint bounds. However, the average temperature for the Base control tends to be cooler than for the Mid and G36 controls. Because of the lack of supply air temperature reset, the Base control keeps the SAT cooler (at approximately 12.5°C) than in the Mid and G36 cases, particularly when the cooling load is low. In addition, the Base control tends to require simultaneous heating and cooling in the winter and spring seasons. This is due to the combination of lack of SAT reset and high terminal box minimum airflow rates. The result is more cold airflow through the system than is required to provide adequate cooling to each zone, and many zones, therefore, using reheat to maintain the zone setpoint temperature. Note that the Base control method with simultaneous heating and cooling showcases a really bad control situation for the VAV system, which represents a not uncommon phenomenon in existing system operations (Rosenberg et al. 2017). Higher energy savings potential of the higher operating hour cases are likely due to extended operating hours in the early morning and late evening. During these times, only partial heating and cooling are generally needed, which is when the G36 control excels the most over the Base control (see Figure 17).

Meanwhile, there is less energy savings potential when a system is using the Mid control. Figures 11 and 15 show that the Mid control cases perform close to those of G36 in many cases. In Figures 16, 17 and 18, both control strategies exhibit no simultaneous heating and cooling and exhibit similar patterns in supply air temperature reset and cooling demand when the outside air temperature is above approximately 16°C (when the outside air temperature is below approximately 16°C, the G36 control tends to call for higher system airflow and higher supply air temperatures, closer to the zone air temperature). The marginal energy savings of G36 compared to the Mid control shows that combinations of the SAT reset, DSP reset, and lower terminal box minimums can lead to very efficient operation. Note that the SAT and DSP reset strategies (particularly the DSP reset) in the Mid control are comparable to the trim and respond G36 strategies and the Mid zone minimum air flowrate of 20% is closer to the 15% or more in the G36 control than the 30% for Base.

6.3. Limitations and future work

Several limitations have been identified in this modelling work, which may lead to inaccurate estimation of the energy savings potential associated with the G36 control.

The fan model was configured with constant hydraulic and motor efficiencies at all air flowrates, leading to the fan power as a function of flowrate to trend towards the origin at constant static pressure setpoints (see Figure 19). The real-life power consumption of a static pressure-controlled fan with a variable speed drive, however, does not follow this trend towards the origin at low flowrates, absent of perfect static pressure reset (Englander and Norford 1992a, 1992b), likely due to a sharp degradation in fan efficiency at low air flowrates. The constant efficiency parameterization used in this study, therefore, likely underpredicts fan power at low air flowrates, especially in cases with no static pressure reset. In future studies, the parameters for the fan hydraulic and motor efficiencies should not be set to constant values, but rather be configured to decrease as the air flowrate decreases.

The unoccupied spaces including storage, restrooms, stairway, and equipment rooms account for 17% of the floor area in the model. Building code often does not require ventilation for some unoccupied spaces such as storage, restrooms and stairways and these spaces are often unconditioned in real life. In this work, those zones are conditioned and controlled the same as other

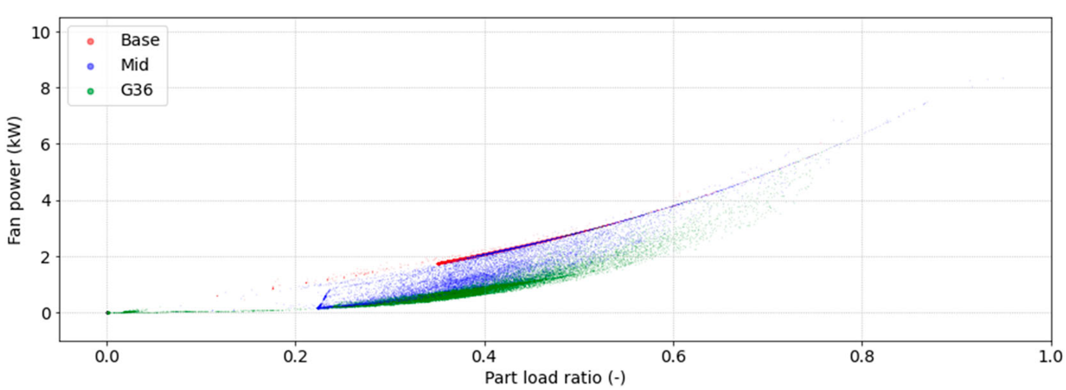

Figure 19. Annual fan operation in Los Angeles, high internal loads and low operating hours, for the three control cases: Base, Mid and G36.

occupied zones. Those assumptions may lead to overestimating the energy use, particularly in the Base case, when a small amount of need for cooling drives the operation of the whole HVAC system.

Some other important factors may also influence the energy savings potential of the G36 control. This could include additional building use types, building floor areas and configurations, envelope construction, climates, and treatment of inter-zone air exchange and infiltration. Meanwhile, for system design and operation, this could include other measures defined by G36, such as the use of occupancy or CO_2 sensors for demand-controlled ventilation or the use of zone groups. In addition, component and system sizing, which are not specified by G36, could influence the energy savings results presented in this paper as well.

7. Conclusion

The ASHRAE Guideline 36-2018 prescribed high-perfor mance sequences of operation for the VAV airside systems. The energy savings potential of retrofitting existing controls to the G36 sequences had yet to be shown for a wide range of cases. This paper evaluated the building HVAC energy consumption using the G36 sequences against a group of baseline controls that represented conventional control practices. The state-of-the-art Spawn simulation tool was used in the simulation studies. Spawn uses EnergyPlus for the building envelope with detailed zoning scenarios, and Modelica for the pressure-flow network of the HVAC system, for HVAC equipment and control sequences. Spawn allows explicit modelling of the control sequences and HVAC system operation using the CDL. The comparison of the control sequences was further conducted in a parametric study with combinations of three climates, three scenarios of building operating hours, and three scenarios of internal load magnitudes. All together, 243 cases were simulated and analysed and 216 pairs of comparisons were conducted for the energy savings calculation.

The simulation results showed a wide range of energy savings potential from 2% to 75% with an average of 31% for the G36 control sequences. The range of savings depends on the baseline control strategy and the comparison conditions, i.e. the climate, building operating hours and internal load density assumptions. Three control strategies played an important role towards the energy savings: supply air temperature reset, duct static pressure reset and zone airflow control, where the duct static pressure reset strategy presented the largest energy savings potential for a singular strategy. Climate and building operating hours had more impact on the energy savings than the internal load density.

Several factors were identified in the modelling assum ptions that may cause inaccurate estimations of the energy savings of the G36 sequences compared with real-life operations, such as potential over-conditioning of unoccupied spaces and an overly-simplified assumption for fan efficiency as a function of part load. Future study of this work could include investigating the G36 energy savings on different building prototypes, climates, and building configurations, additional measures defined by G36, such as demand-controlled ventilation and control of zone groups, and additional system types included by G36, such as a dual-duct VAV system. Future work should consider a more detailed model of plant and plant efficiency, especially in combination with the new plant sequences released with G36 version 2021. Further improvements can also be made on modelling assumptions as well as continuous improvement of simulation tools, as modelling complex controls with conventional simulation engines is still a challenge (Paliaga et al. 2020).

8. Data availability

The models and scripts for simulation, post-processing and visualization used in this work are available at https://github.com/LBNL-ETA/G36SavingsCalculator. This open-source GitHub repository also includes a prototype of an Energy Savings Calculator (Blum and Zhang 2021) implemented in Microsoft Excel spreadsheets. The variables investigated in Sections 4 and 5 are formulated as drop-down lists in cells for users to choose. Additional parameters are included such as building size, heating and cooling system efficiencies, primary and secondary air systems and utility prices. Taking the values and choices input by users, the Calculator estimates energy savings potential of HVAC control retrofits to G36 sequences based on the normalized simulation results in the back-end. The breakdown of energy consumption due to heating, cooling, fan, and electrical appliances are included in the Calculator so that users of the tool can easily see the energy savings source and whole-building energy savings percentage.

Table 5 summarized the main model components from the MBL used in this study. The thermal zone model `Buildings.ThermalZones.EnergyPlus.ThermalZone` is based on the implementation of the MBL GitHub commit 8a57634. The other models are based on the MBL master branch commit c094d27. The implementation of the G36 control sequences in the MBL were initially based on the public review version of the G36 (the package is thus named as G36_PR1 in the library). The sequences are in the final process of updating to the official 2018 version of the G36.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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