Advanced Building Automation Systems

Best Practices Guide

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Preface

This guide was initially developed with funding from the California Energy Commission's Electric Program Investment Charge program as part of the project titled Best in Class: Demonstrating Scalable Operational Efficiency Through Optimized Controls Sequences and Plug-and-Play Solutions.

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Introduction

- Purpose of this Document
- Introduction to Guideline 36
- The Benefit and Promise of Guideline 36
- How to Use Guideline 36

1 Introduction

1.1 Purpose of this Document

Building automation systems (BAS) are a fundamental component in most commercial heating, ventilating, and air conditioning (HVAC) systems. The proper design, installation, and operation of BASs are each critical factors for enabling HVAC systems to perform efficiently while achieving acceptable thermal comfort and indoor air quality. Nevertheless, poorly implemented and operated BASs are far too common in commercial HVAC systems. This guide is intended to serve as a one-stop resource for best practices in the implementation and operation of BASs and to address some of the knowledge barriers to achieving high performance BASs. This document highlights the opportunity around and key elements of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 36 High-Performance Sequences of Operations for HVAC Systems (G36), but it also addresses other key BAS topics that are not included in the scope of G36. It explains how to use G36 as part of a specification, presents the rationale underlying the sequence logic and how the various parts work together to achieve high performance operation, and provides suggestions for specifying, installing, testing, operating, and troubleshooting to achieve success with an advanced BAS project.

This guide is intended for a broad audience, including designers, energy analysts, installers, commissioning providers, and building operators. Building owners and property managers may also benefit from general information presented on the value proposition and retrofit opportunities associated with G36. The document is meant to serve as a reference to help stakeholders better understand main concepts and key issues. Rather than being read from top to bottom, this guide may be most value as a reference to look up additional information on specific topics as questions arise.

1.2 Introduction to Guideline 36

G36 was established in 2018, building upon the final product of ASHRAE research project RP-1455 to develop control sequences that can be readily adapted to provide best-in-class performance for a variety of common HVAC system types. (Hydeman & Eubanks, 2015; Hydeman & Eubanks, 2015)

1.1.1 What is Guideline 36?

G36 is a library of standardized sequence logic for the control of HVAC systems and equipment. The high-performance sequences were established based on a survey of existing logic that has been vetted and improved over decades and, subsequently, through a consensus-based process. G36 is a set of sequences that prioritizes energy efficiency, ease of operation, indoor air quality, thermal comfort, and code compliance. Its initial 2018 release covers single- and multi-zone variable air volume (VAV) reheat air handler units (AHUs) and terminal units. The Guideline is under continuous maintenance, through a process overseen by a committee of volunteers. Members of the public may propose changes to the guideline; proposed changes may then be reviewed and approved by the guideline project committee. The guideline is republished on a triennial basis, incorporating any approved addenda since the last publication. The 2021 publication included numerous revisions, bug fixes, and additions. Most notably, it includes the addition of sequences for hydronic central plants based on the results from ASHRAE research project RP-1711. (Taylor, 2021) Due to the relative timing of publication, the hydronic plant sequences are not addressed in this edition of this Best Practices Guide; however, the air-side sequences that are the primary focus of this document are largely the same between the 2018 and 2021 versions of G36.

As a library, G36 includes multiple options for addressing different types of equipment, code requirements, and climates. For example, the sequences for AHUs include different options for coil configuration, fan control, outdoor air measurement, and ventilation logic.

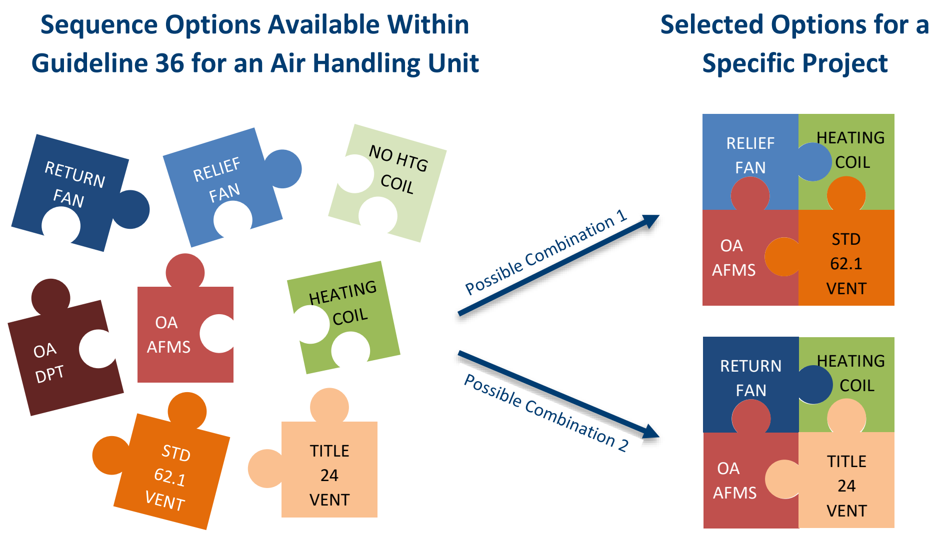


Figure 1. Illustration of Sequence Options with Guideline 36

Figure 1 above shows how one can use G36 to assemble—from pre-tested logic “parts”—a full working sequence for a variety of possible equipment configurations and circumstances.

1.1.2 What Guideline 36 Is Not

The scope of G36 is strictly limited to control sequence logic and supporting tools/information, such as functional test scripts. However, while solid sequences are necessary, they are not in themselves sufficient to achieve good performance and comfort. For example, hardware must be correctly specified, correct installation must be verified by testing, and the graphical user interface must provide essential information in a rational and intuitive fashion. G36 does not address these topics.

Equally importantly, the operators must understand the rationale behind the sequence logic—how and why the different parts interact as they do—to efficiently troubleshoot and effectively maintain the system beyond the warranty period.

As a comprehensive resource for high performance BAS installations, this guide will address this broader scope of considerations and provide suggestions for addressing these sequence-adjacent issues in design documents.

1.3 The Benefit and Promise of Guideline 36

Modern direct digital control (DDC) systems are generally operated with custom programming logic created by the installing contractor. Though most building HVAC systems are generally similar, the current standard industry practice is to develop custom sequences and control programming for each application or to adapt logic from a similar recent project. In addition to the process inefficiency of *reinventing the wheel* for each project, this practice also introduces the risk of problems and operational inefficiencies, such as poorly written sequences or incorrectly implemented programs. G36 helps address this industry issue by providing a collection of standardized, high performance sequences of operation for HVAC systems. Beyond simply establishing a set of best practice sequences, industry standardization around G36 offers a potential for market transformation by streamlining the BAS market processes through design, implementation, and operation. With standardization, BAS manufacturers can centrally pre-program and pre-validate the logic in their software libraries, which would improve quality and greatly reduce effort required on each project for programming and commissioning.

1.1.3 Value Proposition

G36 provides an opportunity to streamline the BAS design, construction, and commissioning processes (See Figure 2 below). By using G36, designers can save on engineering time compared to the business-as-usual approach of developing custom sequences of operation, points lists, and schematics. In construction, the BAS software design and installation effort may be reduced through the use of manufacturer G36 programming libraries (G36 does not address the design of the BAS network or impact the installation of the BAS hardware, which will continue to constitute a significant effort in the construction process). Commissioning may also be streamlined through the use of G36: the use of manufacturer programming that is pre-tested at the factory will reduce the degree of field testing that is required for both the contractor and the commissioning provider.

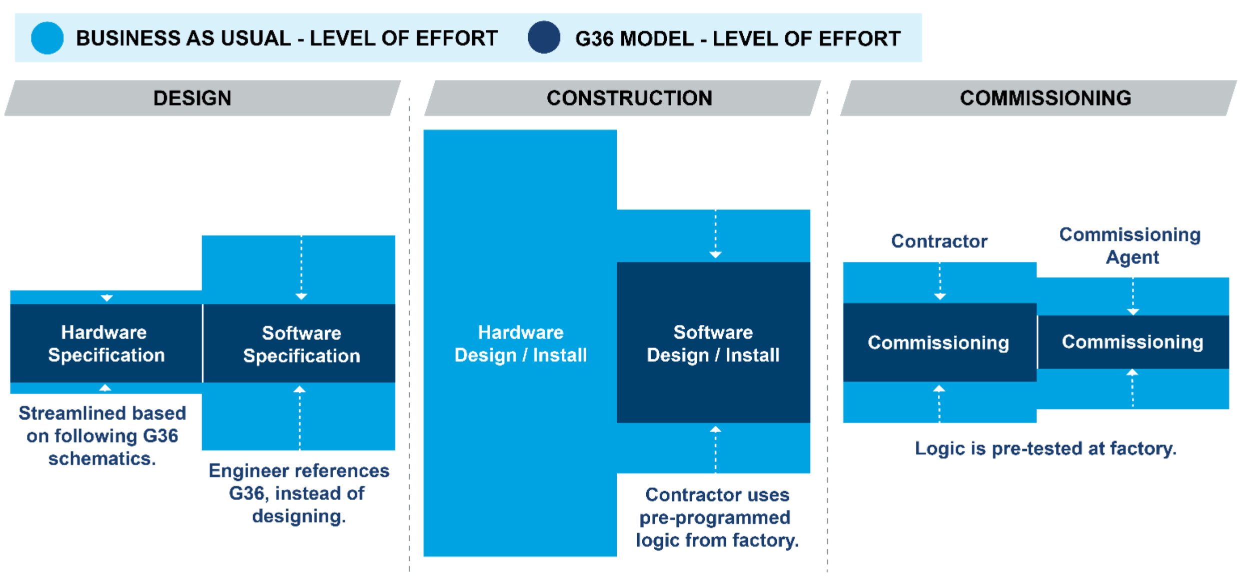


Figure 2. Reduced Level of Effort with Guideline 36

G36 provides value to wide a range of industry stakeholders throughout the design and construction process (See Figure 3 below). At the time of this writing in 2021, almost all major BAS manufacturers have active research and development efforts around centralized G36 application libraries, and a few have publicly released libraries covering at least a portion of the G36 sequences of operation. With G36, facilities management, building owners, design engineers, controls contractors, controls manufacturers, and commissioning providers will secure cost savings, increased revenue, and improved occupant comfort. Building owners will benefit from lower design and construction costs and improved thermal comfort, leading to fewer occupant complaints. Less effort will be required by design engineers, controls contractors, and commissioning providers to design, implement, and test systems, and they will see an increase in customer satisfaction. As a result, controls contractors and commissioning providers can expect an increase in market demand, which can have significant economic benefits such as new jobs. Despite the added value for stakeholders, there are likely to be adoption challenges from disruption to current business practices as stakeholders adapt to new workflows.

	FACILITIES MANAGEMENT	OWNER/ CUSTOMER	DESIGN ENGINEER	CONTROLS CONTRACTOR	CONTROLS MANUFACTURER	COMMISSIONING AGENT
Energy		Reduced energy use & costs				
Implementation Effort	Reduced staff training & maintenance cost	Lower design & construction costs	Less effort to design	Less effort to implement		Less effort to test
Occupant	Fewer occupant complaints	Improved thermal comfort				
Building operations	Improved operations	Higher quality				
Market share				Increased market demand		
Customer satisfaction			Increased customer satisfaction			

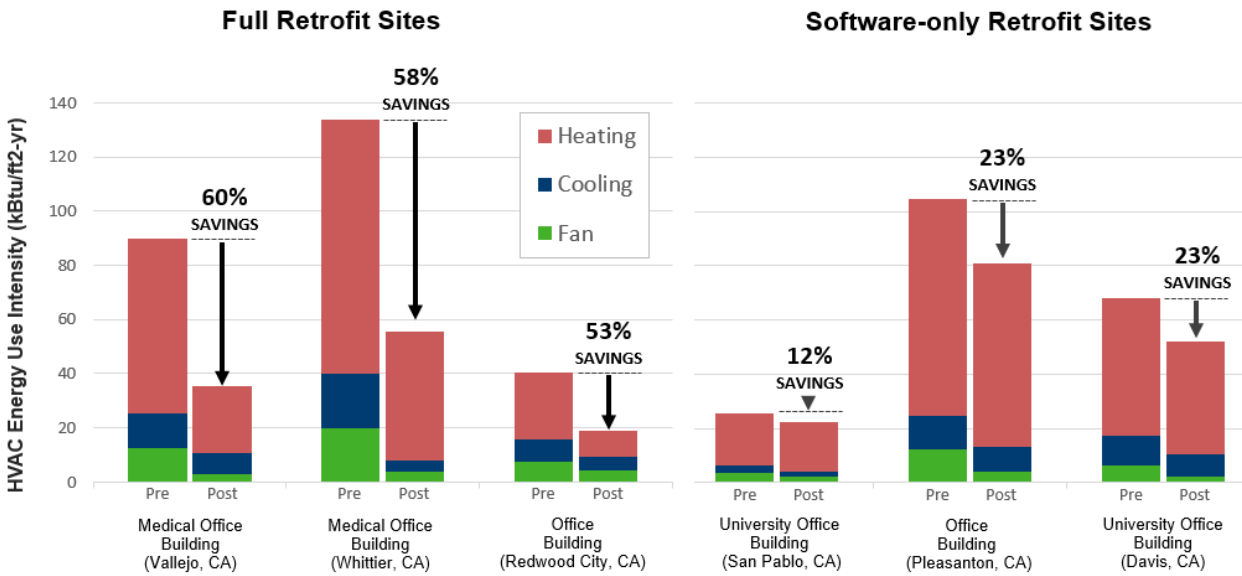
Figure 3. Guideline 36 Benefits Across the HVAC Industry

1.1.4 Energy and Indoor Environmental Quality Benefits

Energy Benefits

The significant potential for energy savings with using G36 has been well documented in field demonstrations and simulation studies.

A large demonstration study funded by the California Energy Commission (CEC) evaluated the impact of retrofitting existing buildings with G36. Two types of retrofits were evaluated: full control retrofits (where BAS hardware and programming replaced) and software-only retrofits (which focused only on re-programming the control logic). (Cheng, Singla, & Paliaga, 2022) Figure 4 below shows the HVAC energy use intensities pre and post retrofit for full retrofit and software-only retrofit sites, with energy end-uses are broken out. For each retrofit type, two demonstration sites are shown, as well as another a similar project that was not part of the demonstration. The full retrofit sites each achieved about 50 to 60% reduction in HVAC energy intensity. Note that the medical office buildings (MOB) generally have a much higher energy intensity than non-MOBs. The roughly 80% fan savings at the MOB projects (both full retrofits) is striking, shown in the reduction of the green bars. The Vallejo project was awarded a national ASHRAE technology award in 2021. (Kiriu & Stein, 2021) Among the software-only retrofit sites in Figure 4, the HVAC energy savings are also consistent within a range of 10 to 25%. Although the overall savings are lower than compared to the full retrofit sites, the first costs and level of disruption are also much lower. All of the retrofits shown had simple paybacks of eight years or less.



(Cheng, Singla, & Paliaga, 2022)

Figure 4. Guideline 36 Retrofit Energy Savings

For the retrofit projects that included full BAS hardware and software updates, the HVAC energy savings were very comparable from 50 to 60%, with 50 to 60% heating savings, 40 to 80% cooling savings, and from 40 to 80% fan savings. Where control hardware replacements are included (e.g., economizer dampers/actuators and control valves), some of the energy savings may be due to these retro-commissioning type activities. For the retrofit projects with AHU and zone level software retrofits (only reprogramming of control logic), the HVAC energy savings ranged from 10 to 25%, with 4 to 18% heating savings, 26 to 35% cooling savings, and 38 to 65% fan savings. Although the energy savings are lower with these software-only retrofits, the implementation costs were also significantly lower. Implementation costs, and payback periods, will be even lower once BAS manufacturers have preprogrammed the G36 sequences for their dealers.

Table 1 below provides a summary of results from HVAC control retrofits to show the range of savings and end use breakdowns across a variety of different projects. The retrofit scope columns indicate the nature of the retrofit project (e.g., software-only retrofits may only have revisions to AHU and/or zone control logic, and some sites underwent HVAC equipment and/or BAS hardware retrofits as well). Savings reported are generally based on normalized measured energy consumption techniques. Where end-uses are not directly measured (e.g., HVAC electricity may encompass both fan energy and cooling plant energy, or whole building electricity may encompass HVAC, lighting, and plugs loads), assumptions are made based on benchmarking data[1]. Cooling and heating equipment efficiencies are also assumed where only energy consumption was directly measured. Where available, actual utility rates are used (excluding demand charges) or otherwise representative energy rates are used to evaluate savings. Simple paybacks are based on actual or estimated implementation costs, where available.

The energy savings associated with each project is very much dependent on the existing system configuration and operation, among myriad other factors. In general, the existing condition for each of

[1] Assumptions of end-use breakdowns are based on data for applicable building types from the California Commercial End-Use Survey Consultant Report (CEC-400-2006-005)

the sites shown in Figure 4 included single maximum VAV logic with high zone minimum airflows, and either fixed setpoints or rudimentary reset approaches for supply air temperature (SAT) and duct static pressure control. The site with low heating savings is notable as the pre-existing control operated with unusually warm SATs. That operation minimized reheat energy (hence the very little heating savings) but with a significant fan penalty associated with the much higher airflow requirements to meet the cooling loads (fan laws dictate that fan power increases with the cube of airflow).

Table 1. HVAC Control Retrofit Energy Savings Comparison

Building	Project Parameters / Retrofit Scope								Site Energy Savings							Energy Cost Savings ($/ft2)			Economics
Site	Size (ft^2)	ASHRAE CZ	Cooling Type	Heating Type	HVAC Equip	BAS Equip	BAS AHU Logic	BAS Zone Logic	Fan	Cooling	Heating	Total HVAC	Whole Building Electric	Gas	Whole Building	Whole Building Electricity	Gas	Total	Overall Payback (yr)
Vallejo MOB	200,000	3B	CHW	HW	X	X	X	X	78%	40%	61%	60%	26%	61%	45%	$0.62	$0.44	$1.06	8.0
Whittier MOB	34,000	3B	DX	HW	X	X	X	X	81%	81%	49%	58%	35%	49%	42%	$1.24	$0.50	$1.74	5.5
Office Building	142,000	3C	DX	HW		X	X	X	41%	41%	60%	53%	15%	60%	32%	$0.22	$0.14	$0.37	6.3
Academic Bldg	140,000	3B	CHW	HW			X	X	63%	26%	18%	23%	24%	18%	21%	$0.54	$0.10	$0.64	--
CCC SAB	41,000	3B	CHW	HW			X	X	38%	35%	4%	12%	11%	4%	8%	$0.13	$0.01	$0.14	7.0
KPPDC	23,700	3C	CHW	HW			X	X	65%	27%	15%	23%	17%	15%	16%	$0.50	$0.13	$0.63	1.8
Yahoo A (RP-1515)	180,700	3C		HW				X	8%	8%	16%	14%	3%	16%	9%	$0.04	$0.03	$0.07	--
Yahoo B (RP-1515)	180,700	3C		HW				X	20%	20%	19%	19%	7%	19%	11%	$0.07	$0.02	$0.09	--
Yahoo E (RP-1515)	212,600	3C		HW				X	17%	17%	9%	12%	6%	9%	7%	$0.09	$0.02	$0.11	--
Yahoo G (RP-1515)	79,700	3C		HW				X	9%	9%	4%	5%	3%	4%	4%	$0.02	$0.01	$0.03	--
800 Ferry (RP-1515)	20,000	3B		HW				X	43%	29%	6%	17%	14%	6%	11%	$0.18	$0.01	$0.19	--

(Cheng, Singla, & Paliaga, 2022)

The five sites with only zone logic retrofits were part of ASHRAE research project RP-1515, where the only change was to reduce zone minimum airflows from a baseline condition of 30% (as a percentage of zone cooling maximum airflow) down to the ventilation minimums (according to California Title 24 requirements). (Arens, et al., 2015) The HVAC savings from this simple measure ranged from 5 to 22%, indicating that the zone logic is responsible for a significant portion of the energy savings with the more-comprehensive control retrofits. Two key points follow from this finding:

1. The importance of dual maximum VAV logic and low VAV minimums, which are prescriptively required in California Title 24 and ASHRAE Standard 90.1.
2. The opportunity to readily achieve very cost effective savings through retro-commissioning efforts that target zone airflow and control logic.

Few simulation studies have evaluated the energy savings potential associated with G36, presumably due to the lack of capability for conventional simulation tools to accurately model advanced control sequences. Software tools based on the DOE-2 and EnergyPlus simulation engines can only model simplified control strategies, though the energy management system module in EnergyPlus does allow for custom scripting to simulate some advanced control strategies.

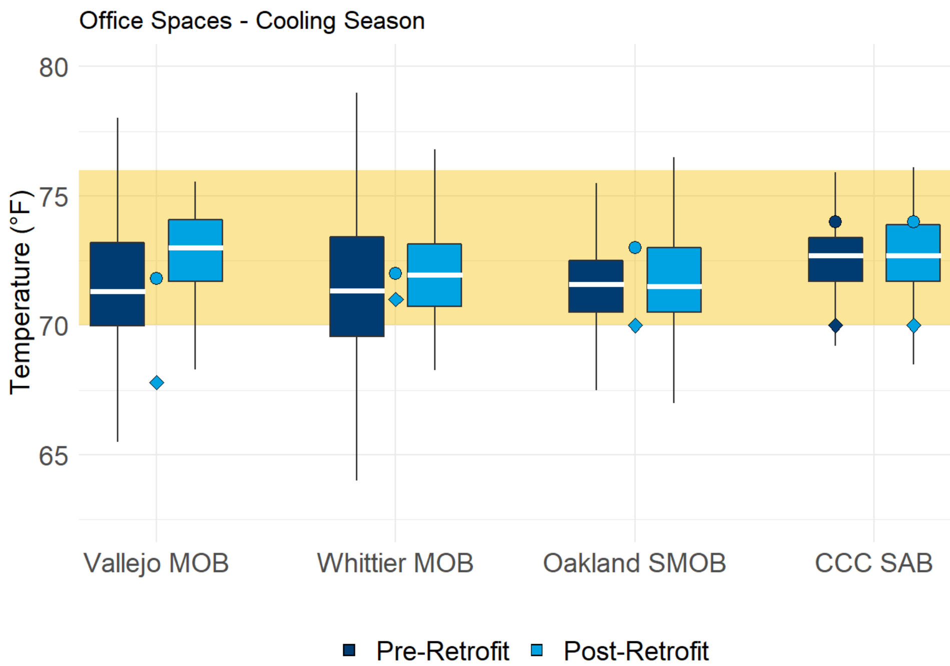
A simulation study evaluated the impact of various control strategies with VAV reheat systems, varying each measure between three levels: good, average, and poor practice (Pang, Piette, & Zhou, 2017). The study showed that the energy performance of VAV systems can vary significantly based on system controls, by over 60% in the modeled cases, underscoring the importance of clearly defining system controls when describing VAV systems. The implication on real life is just the same: the careful design and installation of HVAC control systems is critically important and has a great impact on building energy performance. The OpenBuildingControl project developed a new *control description language* in Modelica that allows for the explicit simulation of advanced control strategies. Coupled with EnergyPlus, the tool found that G36 saved 35% of HVAC site energy compared to a single basecase building (Wetter, 2021). A parametric simulation study using a similar co-simulation between EnergyPlus and Modelica found average HVAC energy savings of 31% based on a range of baseline conditions in California climates. (Zhang, et al., 2022)

Indoor Environmental Quality Benefits

Occupant discomfort due to summertime overcooling is a widespread problem in commercial buildings with VAV reheat systems. ASHRAE research project RP-1515 showed that this negative thermal comfort impact is largely due to zone minimum airflows that are set unnecessarily high (often 20 to 50% of the cooling maximum). Reducing these minimums to minimum ventilation requirements (as low as 10% of maximum) achieved total HVAC savings of 10 to 30%, but it also achieved significantly reduced occupant dissatisfaction in the warm season. (Paliaga, Zhang, Hoyt, & Arens, 2019; Arens, et al., 2015) See discussion in Section 3.4.2.

The indoor environmental quality impact from control retrofits was evaluated as part of a CEC demonstration study. Researchers expected that improved system resets and lower zone airflow minimums would result in decreased summer over-cooling and improved occupant thermal comfort. However, results showed that space temperatures were relatively similar before and after the retrofits. (Cheng, Singla, & Paliaga, 2022)

Figure 5 below shows box and whisker charts representing cooling season zone temperature data in office spaces before and after control retrofits at four different demonstration sites. The boxes show the range of temperatures in the interquartile, between the 25th and 75th percentiles. The whiskers represent the full range of temperatures recorded, and the median temperatures are shown by the white line. Where zone heating and cooling setpoint data are available, they are represented as diamonds and circles, respectively. At three out of the four sites, thermostat setpoints were not available for the pre-retrofit period, so the setpoints shown are shown between the pre- and post-retrofit bars and are based on the post-retrofit trends. At two sites, the zone temperatures were slightly warmer after the retrofit; at the other two sites, the zone temperatures were unchanged. The RP-1515 project found that even an average space temperature increase of 0.4°F in the summer within the ASHRAE comfort region cut occupant cold discomfort in half, suggesting that the difference in average space temperatures seen at KP Vallejo MOB and KP Whittier MOB likely resulted in improved occupant thermal comfort in those areas. (Arens, et al., 2015)



(Cheng, Singla, & Paliaga, 2022)

Figure 5. Thermal Comfort: Zone Temperatures Before and After Guideline 36 Retrofit

1.1.5 Challenges, Barriers, and Solutions

Though publication of G36 and demonstrations of the potential benefits are strong first steps toward encouraging the use of G36, there are a number of challenges and barriers that may impede its successful deployment at scale.

Table 2. Challenges, Barriers, and Solutions

Challenge	Solutions
Difficult to understand: The G36 sequences are complex. Applying and adapting the sequences to site-specific conditions for individual projects may require more technical understanding than most HVAC designers possess.	This Best Practices Guide partly addresses this challenge by explaining how key sequences work and key considerations for designers. In addition, there are trainings and workshops hosted around the country each year, including some online resources (see Section 7).
Difficult to use: The process of editing the sequences correctly in Microsoft Word®, while maintaining technical intent and integrity of active hyperlinks and references requires care and detailed spec-editing abilities. The 2018 version of G36 was only available for purchase in a PDF form, which further complicates editing.	Efforts are underway as of this writing to develop a sequence selection software tool for G36. In the meantime, the guideline is now available as a Microsoft Word® document for the 2021 version of the Guideline, to facilitate editing for projects.
Difficult to program: On typical projects, only basic sequences of operation (SOOs) are provided, and contractors expect to largely reuse programming from similar past projects. Contractors may not even look at SOOs when bidding. The level of detail	As of this writing, most of the major manufacturers are developing factory programming libraries based on G36, and a few have publicly released programming for at least a portion of G36.

Challenge	Solutions
and complexity of the SOOs may require a higher level of effort than for typical projects.	
Value proposition is not clear: Industry stakeholders may not understand the benefits of using G36 or have concrete data demonstrating these benefits to be real and achievable.	Recent field demonstrations and simulation studies show clear energy and cost savings. Other values will be developed as the guideline gets more market penetration.
Lack of awareness: G36 was only recently published, and much of the industry is unaware of its existence.	Knowledge of G36 is currently being disseminated through industry organizations such as ASHRAE, at both the national and chapter level meetings. Many BAS manufacturers are promoting their G36 efforts. Utility programs that leverage G36 are a potential solution, which could significantly raise awareness.
It is new: The construction industry is slow to adapt to change.	Awareness and interest in G36 are growing rapidly. Multiple recent and active research and demonstration studies will enhance and highlight its benefits. Efforts by manufacturers to develop central G36 libraries will help to quickly normalize it to dealers and installers. Many large building portfolio owners have incorporated G36 into their design standards, which will further accelerate industry acceptance and adoption.
Scope of G36 is limited: The initial version of G36 only included sequences for certain airside systems, and G36 only addresses the sequences themselves, but it does not include guidance on other key control design and operational issues.	The publication of G36-2021 included sequences for additional equipment types, including hydronic systems. ASHRAE is actively supporting development of additional sequences, both through research projects as well as volunteer committee efforts. This Best Practices Guide provides guidance on other key HVAC control issues that are beyond the scope of G36.
Complex for operators:	This Best Practices Guide partly addresses this challenge by explaining how key sequences work, providing a troubleshooting guide to suggest how to address operational issues and offering examples of effective BAS graphics. The standardization of sequences and preprogramming by manufacturers will also improve the implementation of the sequences, which will reduce the tendency of operators to override controls perceived as not operating properly.

1.1.6 Future Form

The current industry delivery process for control logic is a high-risk process that usually leads to sub-optimal performance. The status quo process has many steps that are manual and customized per project, and it is highly dependent on the expertise of individual engineers, controls technicians, and commissioning providers. Figure 6 below shows the controls project flow through the various stakeholders, with high-risk steps (manual and/or error prone) identified in the status quo process.

Standardization around G36 reduces many of these risks. The current G36 process represents best practice today with reduced risks when project specifications use G36, and contractors follow the guideline using programming that has been developed by the manufacturer. Each manufacturer will develop and maintain a library of G36 programs for their platforms as the guideline evolves; local dealers and installers would not need to do this programming on each project. The G36 sequences rely on complex and advanced logic to achieve high performance – though this complexity might present implementation concerns for typical projects executed through standard practice, risks can be minimized through the use of robust and pre-validated logic from the manufacturers. In the future, development of software tools and expanded industry standardization may further streamline this process and eliminate risk at the various steps. (Cheng, 2021) Ongoing development of selection software will automatically generate project-specific sequences from G36 based on a simplified set of user selections. This same tool may eventually output associated functional tests. Manufacturer software will generate programming from a library of pre-programmed and pre-validated logic. Standardization offers the potential that a machine-readable G36 model number could unambiguously indicate which options are selected. This model number could be output by the selection software and input into the manufacturer software to eliminate the need for human interpretation in the process of generating G36 programming. Overall, this process reduces effort, improves quality, and streamlines the overall product delivery chain.

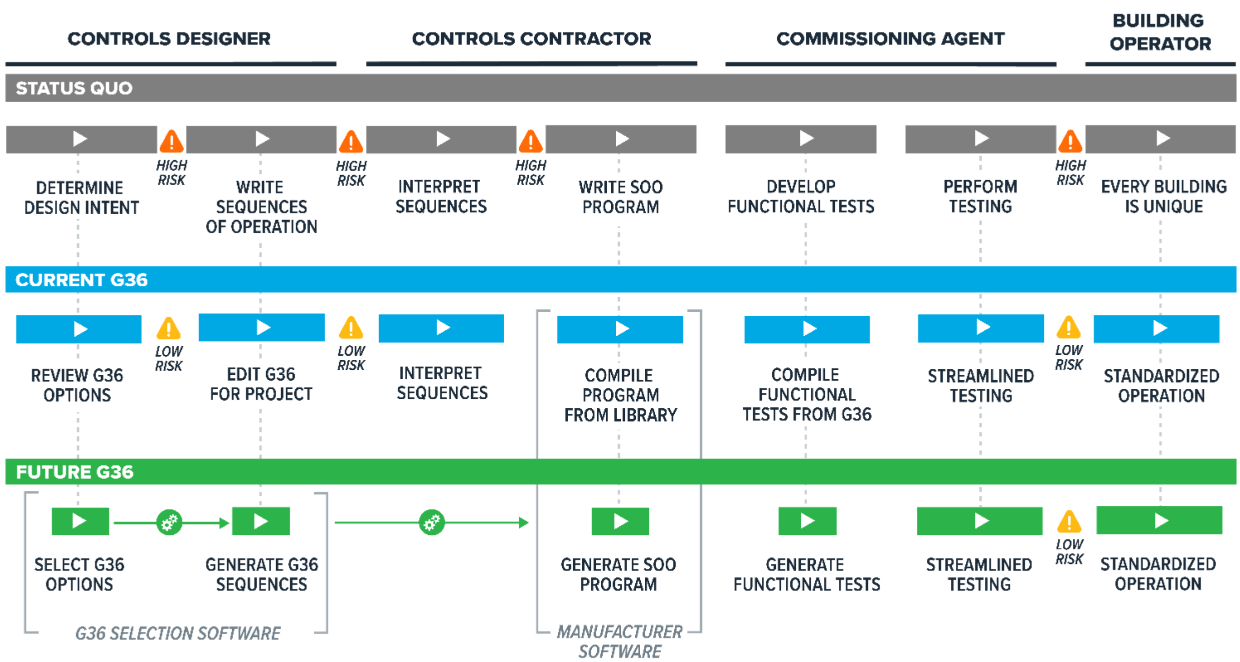


Figure 6. Current and Future Models for BAS Market Delivery

2

Understanding Guideline 36

- Document Structure
- Guideposts for Guideline 36: Formatting
- Variable Naming: Design Values vs. Control Values
- How to Specify Guideline 36 Sequences

2 Understanding Guideline 36

2.1 Document Structure

Beyond the title, purpose, and scope, the Guideline consists of several parts:

- ***Part 3: Set Points, Design and Field Determined*** describes the setpoints and other parameters that must be specified by the design engineer, or determined during construction by the testing, adjusting, and balancing (TAB) or controls contractor.
- ***Part 4: List of Hardwired Points*** includes points lists for all system types addressed by the Guideline.
- ***Part 5: Sequences of Operations*** contains the control logic itself, organized by the type of equipment.
- ***Informative Appendix A*** has control diagrams that correspond to a subset of the Part 4 points lists.

Parts 3, 4, and 5 of the Guideline are intended to be edited and issued together as part of a specification under Division 23 or Division 25 and are formatted accordingly, with paragraphs numbered in a hierarchical list (e.g., 5.1, 5.1.1, 5.1.2, 5.2, 5.2.1, etc.).

Note that these paragraph numbers are also used for internal cross-referencing, and they are *live* links (i.e., click to jump to the destination) in the original Guideline document. Preserving these links (e.g., when creating a PDF) is highly recommended, as it makes the document much easier to navigate. A contractor who receives the sequences as hardcopy or embedded in a larger PDF should ask the engineer to provide a digital copy of the original source document.

2.2 Guideposts for Guideline 36: Formatting

In addition to the main body text, the Guideline uses two types of special formatting to help guide the user.

The first type of special formatting is for **Informative Notes**, which explain the rationale behind the sequence logic or provide supplemental information. Here is the description of Informative Notes from G36, which uses the Informative Notes formatting:

> *Notes in italics between thin lines provide guidance or additional information about specific sequences.*
>
> *These notes are not a part of this guideline. They are merely informative and do not contain requirements necessary for conformance to the guideline.*

Informative Notes are not part of the specification but are potentially useful to the design engineer, contractor, and commissioning provider, as they provide rationale behind key design decisions. The user should decide whether to retain, retain some but not all, or to delete all of the Informative Notes when the sequences are issued. Choosing to retain Informative Notes has the potential downside of making the overall sequence longer.

The second type of special formatting is for **Instructional Notes**, which call out choice-points, where the control logic that is appropriate to the specific project must be identified. Typically, this is a multiple-choice opportunity (e.g., Choose one of paragraphs A, B, or C and delete the other two choices). Here is the description of Instructional Notes from G36, which uses the Instructional Notes formatting:

> **Notes in bold between thick lines provide direction to the editor of these sequences so that they are properly implemented (e.g., identifying mutually exclusive options).**

In the AHU sequences, for example, Instructional Notes identify the places in the document where the engineer should specify whether the AHU uses a relief fan, a return fan, or passive relief. Instructional Notes should generally not remain in a copy of a sequence that has been edited.

2.3 Variable Naming: Design Values vs. Control Values

For ease of representation, many of the operating parameters required by the BAS are referred to in G36 as named variables. For example, the value of **DesMinOA** is the outdoor air requirement at the air handler when all zones are fully occupied.

In many cases, the value used for control is reset from the design value by system conditions. In those cases, the variable being used for control is represented by adding a "*****" ("star") to the variable name.

For example, **DesMinOA** is a fixed value determined during design and conveyed on the AHU schedule. However, the actual outdoor air requirement may be reduced if, for example, only part of the building is Occupied. This value—the one being used for control—is represented by the variable **DesMinOA*** (i.e., "DesMinOA-star"). Within the sequences, this relationship is established by stating that **DesMinOA*** shall equal **DesMinOA** except under specified conditions (such as partial occupancy).

This convention is used throughout the Guideline.

2.4 How to Specify Guideline 36 Sequences

As noted above, Parts 3, 4, and 5 of the Guideline are intended to be issued together as a control logic specification under Division 23 or 25. However, the Guideline as published by ASHRAE is not sufficient by itself: additional information is necessary in order to program the BAS for a specific project.

An array of project-specific information such as zones groups, schedules, and setpoints must be provided. For ease of reference, the required information is consolidated in Part 3 "Setpoints, Design and Field Determined". The majority of these parameters (under "Design") are determined by the specifying engineer and are issued with the construction documents. However, a few of these parameters ("Field Determined") need to be established during construction, in collaboration with the TAB contractor. (These items should be called out in the TAB specification as well as in the control specs, so they are included in the TAB contractor's bid.)

Within the sequences themselves (Part 5 of the Guideline) the Instructional Notes identify the choice-points, where the control logic most appropriate to the project must be selected. The choice of "most appropriate" logic is a function of equipment selection (e.g., does the AHU have a return fan or a relief fan?) and of prevailing code (e.g., is ventilation in accordance with ASHRAE Standard 62.1 or California Title 24 requirements?).

There are potentially three approaches to how the Guideline is used by a specifying engineer for project-specific application:

1. **Edit the Guideline directly to only include applicable sections.** This editing process entails deleting G36 control logic that does not apply and potentially inserting custom project-specific sequences. Starting with the 2021 version, G36 is available as an editable Microsoft Word® document to facilitate this approach. This method results in a single complete and conformed sequence of operation that minimizes ambiguity and maximizes the likelihood that the designer's intent will be realized in the programming. The Instructional Notes in the Guideline indicate that this is the intended approach to using G36. Editing the document, however, can be a challenging process that requires technical understanding of the controls design issues, moderate proficiency with Microsoft Word®, and careful attention to detail. With pre-programming of G36 logic, differentiating native G36 sequences from custom project-specific sequences becomes important, so installers can readily identify what existing programming can be used without modification and what customizations to the programming are required; this can potentially be done with different color fonts or using the track changes mode in Microsoft Word®. Future development of a software tool that provides edited G36 sequences will significantly simplify and streamline this process.
2. **Specify the use of Guideline 36 by referencing applicable sections.** This approach indicates portions of G36 that apply to a specific project by referencing applicable sections (e.g., "VAV Reheat Boxes: Fully comply with ASHRAE Guideline 36-2018 Section 5.6 except as otherwise noted"), rather than directly editing the guideline. Along with references to portions of G36, the project sequence would include any modifications to G36 and any custom project-specific sequences that may apply. Compared to directly editing the Guideline, the resulting project specification would be shorter, and this approach has the potential to reduce the level of effort and understanding required by the designer. An advantage of this approach is that it is unambiguous as to which sequences are directly from G36 and which are not; where installers are leveraging pre-programmed G36 libraries, this distinction may simplify the programming effort. Ultimately, a conformed sequence of operation is still needed for the installer, commissioning provider, and operator—this approach potentially just shifts that process to the controls contractor, who may have more technical understanding of sequences of operation than the designer. The responsibility of developing the full conformed sequence should be clearly identified upfront in BAS specifications to avoid a scope gap. A disadvantage with this approach is that there is no consolidated sequence included in the design document, which makes quality control more difficult.
3. **Require the use of Guideline 36.** Some engineers may prefer to make the controls contractor fully responsible for the details of the control logic (and perhaps the detailed design of the control system), and will simply specify the use of G36 sequences with no additional information. In that case, it becomes incumbent upon the contractor to identify the appropriate control logic, the required setpoints, and potentially the necessary hardware and inputs and outputs. Much of this information can be gleaned from the mechanical schedules, and the Instructional Notes in the Guideline provide guidance where choice-points are required.

However, this approach leaves ambiguity in the scope of work that may lead to inconsistent assumptions made by competing bidders. This approach places a heavy burden on the controls contractor, which may be a project risk if they are not prepared for or did not bid expecting the required level of effort. A scenario where this approach may be suitable is if the designer is unfamiliar with controls design and it is better to instead defer the detailed controls design decisions to the contractor.

The goal in any case is for the installer to be able to identify *a specific control logic sequence corresponding to every piece of non-identical* equipment that is in their scope (This is particularly true for air hander logic, as that logic contains a very large number of choice-points). Ideally, the specifying engineer will provide this information with the drawings and specs, but further coordination and requests for information should be utilized to address any gaps, conflicts, and interpretations required to provide a complete and functioning system.

The installer must have a specific control logic sequence for each piece of controlled equipment.

Key Responsibilities	
Designer	**Contractor**
• Produce complete sequence of operations • Provide project-specific information such as zones groups, schedules, and setpoints • Make all decisions at choice-points in G36	• In collaboration with TAB, determine setpoints that need to happen during construction • Communicate with the designer to clarify any ambiguities
Shared	
• Meet early in construction to review the design intent of the HVAC system • Coordinate with commissioning provider as early as possible	

3

Key Control Sequences In Guideline 36

- Organization of Part 5: Sequences of Operations
- General Control Logic
- Generic Zones & Zone Groups
- Terminal Unit Control Logic
- Control of Multiple-Zone Air Handling Units
- Control of Single-Zone Air Handling Units

3 Key Control Sequences in Guideline 36

The heart of a BAS, and the key to good performance, is the correct implementation of high-performance sequences of operations. Guideline 36 includes a variety of sophisticated control strategies, bringing together established methods from practitioners across the industry as well as novel strategies that are the product of recent research. This section does not recapitulate the Guideline sequences in their entirety, but it instead focuses on presenting the background and explanation of sequences that are key to maximizing energy efficiency with G36.

3.1 Organization of Part 5: Sequences of Operations

The first four sections of Part 5 in the Guideline are “General”, “Generic Ventilation Zones”, “Generic Thermal Zones”, and “Zone Groups”. These sections include control logic and concepts that apply to the system as a whole, rather than to any specific piece of equipment. As such, all four sections should be included whenever sequences are issued for a project. Note that “Generic Ventilation Zones” includes a single choice-point for ventilation control strategy, and it is important that the design engineer specify this.

Subsequent sections of G36 provide control logic for different types of terminal units. For some types of equipment (e.g., dual duct terminals) there are several distinct sequences, representing different control strategies. There are few choice-points in this part of the sequences.

The first four sections of the Guideline 36 Sequences of Operations specify system-level requirements for all projects.

Immediately following terminal unit sequences is control logic for different types of VAV AHUs, including single-zone, multiple-zone, and dual duct. To support a variety of equipment configurations (e.g., return fan vs. relief fan), this part of the sequences includes many choice-points and their accompanying **Instructional Notes**. *It is essential that the design engineer identify <u>and communicate</u> which control logic options are applicable to the project.* Ensuring that this information is communicated in drawings and specs will save many hours of time, many requests for information (RFI), and will make a successful project outcome much more likely.

3.2 General Control Logic

The General section specifies requirements that apply to all control logic within a project, and it introduces several concepts and control strategies that are used throughout the rest of the sequences. A few of these are unusual, and they merit particular discussion.

3.2.1 All Parameters Are Adjustable

All parameters in G36 are adjustable by the user, aside from physical constants and conversion factors that should be hard-coded. Since all other parameters should be adjustable, G36 does not call out specific points as being adjustable. However, all setpoints, timers, deadbands, gains, etc. are available for adjustment by the operator. This gives knowledgeable operators greater control over their system and reduces their dependence upon a service technician.

> Operators and commissioning providers should not use setpoint adjustment to perform testing/commissioning, due to the high risk of a testing adjustment being inadvertently left in place. For testing/commissioning, use overrides instead.

3.2.2 All Points Can Be Overridden

The BAS must be programmed such that all hardware input and output points and all software points/variables, can be overridden by the operator (except life-safety points). This is essential to effective commissioning and troubleshooting. Many BAS products have this capability natively; others require that hardware points be mapped to software points to enable this.

As a best practice, **overrides should automatically expire** after a period of time, **overridden points should be clearly identified** as such in the user interface, and **the operator should have the capability to generate a report of all overridden points** in the system. However, these features were deemed “user interface” elements outside the scope of G36, so this requirement should be included in other Division 25 specifications.

3.2.3 Variable Frequency Drive Speed Points & Limits

To avoid confusion, G36 requires that variable frequency drive (VFD) speed be treated as a percentage value 0 - 100% rather than as motor frequency (Hz). A speed of 0% means the equipment is fully stopped, while 100% speed is mapped to the maximum operating speed of the device, and a non-zero minimum speed is specified as a non-zero percentage value (Figure 7).

This approach supports motors and fan arrays with design speeds that are greater or less than 60Hz in a seamless fashion. It also avoids the confusing situation that can otherwise occur, where equipment operating at minimum speed reports a speed of zero.

This principle should apply both to the speed values exposed to the user and the internal logic of the BAS. Motor frequency should never appear in BAS programming except as it is being converted to a percentage value.

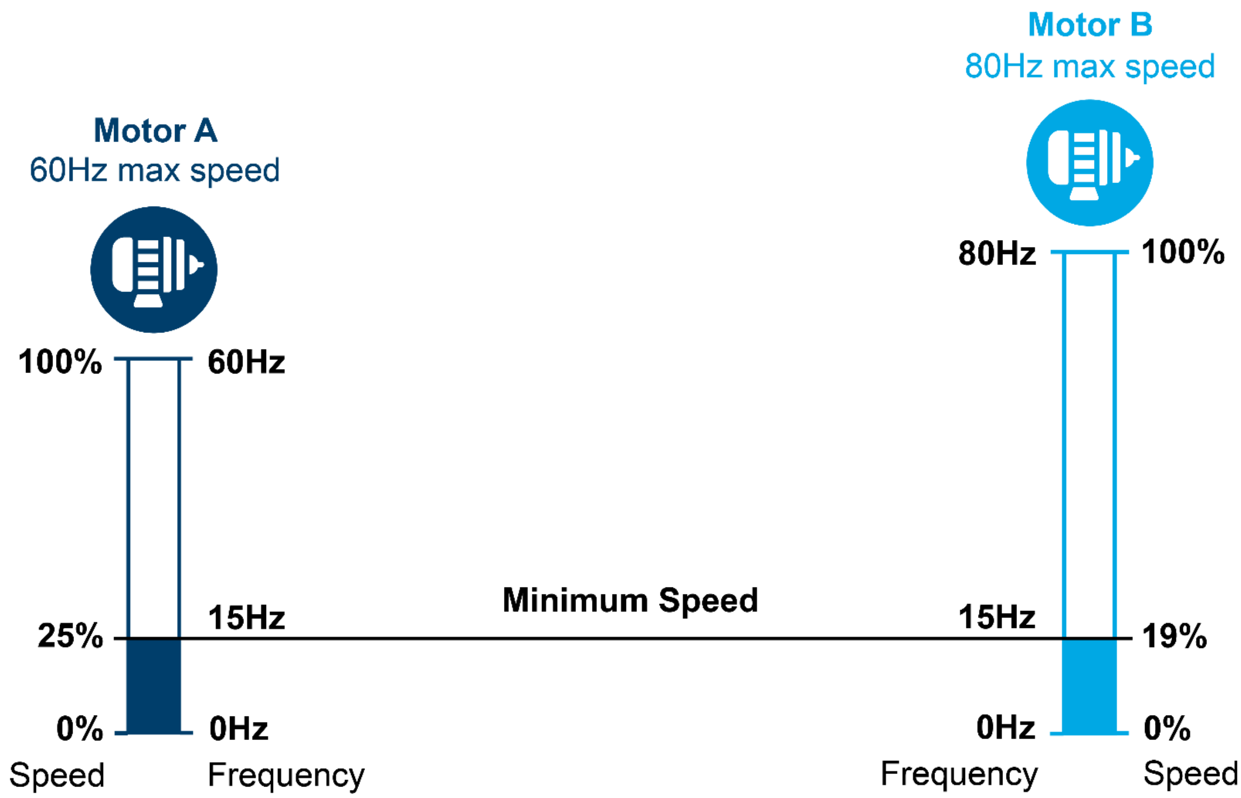


Figure 7. Motor Speed as a Percentage is Unambiguous

3.2.4 Alarm Capabilities, Alarm Suppression

G36 contains several measures to manage alarms and protect the operator from being overwhelmed by alarms. The General section does not define alarms for specific equipment. Those details, including the alarm point, threshold, and level are described in the zone and AHU logic presented later in the Guideline. Instead, this section defines concepts and establishes default behaviors, which should be applied to all alarms unless otherwise noted.

The Guideline classifies alarms according to the ASHRAE standard four alarm levels and establishes **default alarm behaviors** at each level. These defaults include entry and exit delays, latching, how alarms are acknowledged, and post-exit suppression. Applying these defaults project-wide creates a consistent and predictable user experience for the operators.

G36 also includes logic for **Hierarchical Alarm Suppression**, which is based on the idea that if you have simultaneous alarms in both *upstream* and *downstream* equipment, the downstream alarm is likely a consequence of a fault at the upstream equipment. Accordingly, the downstream alarms are suppressed until the upstream fault is remedied. This prevents a situation where, for example, an AHU (the upstream equipment) that experiences a fan failure generates spurious alarms at each of dozens of downstream VAV boxes (Figure 8).

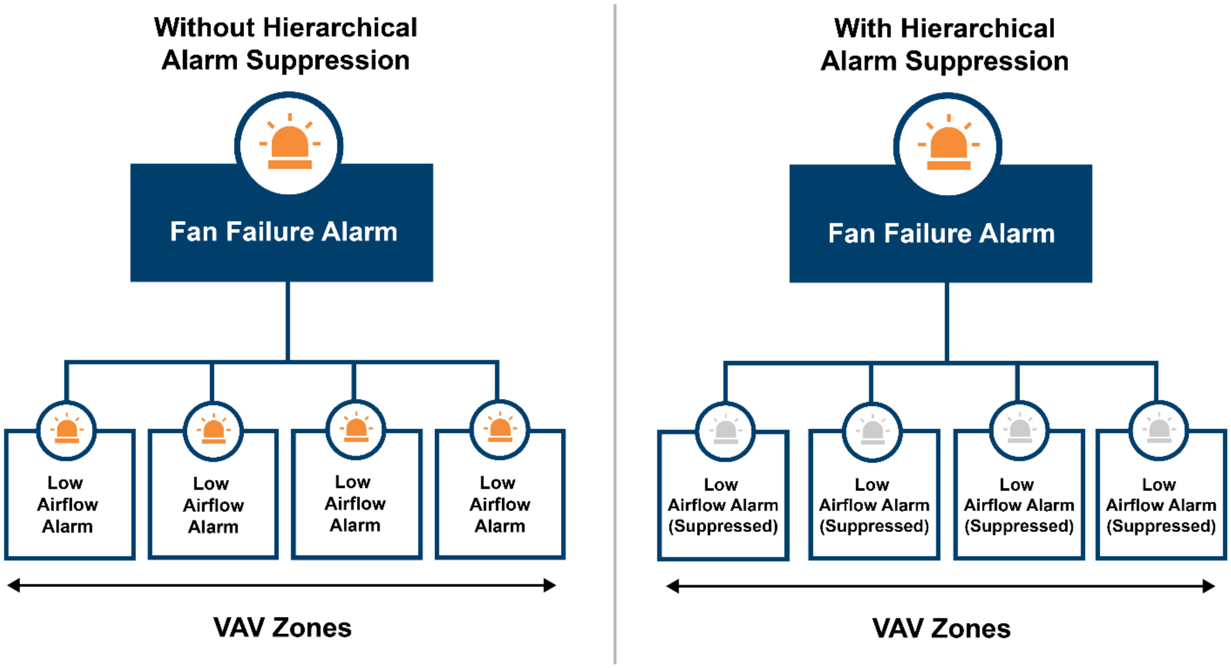


Figure 8. Hierarchical Alarm Suppression Reduces Nuisance Alarms

Functionally, this requires the HVAC system to be defined in terms of upstream/downstream relationships (“source” and “load” are the terms used in the Guideline). For some BAS, these relationships are defined inherently as part of the configuration process; for others, these relationships must be explicitly programmed.

Finally, **Time-Based Alarm Suppression** prevents nuisance alarms associated with an abrupt change in setpoint by suppressing zone temperature alarms for a period of time proportional to the magnitude of the setpoint change.

3.2.5 Trim and Respond Setpoint Reset Logic

Trim & respond (T&R) is a method for resetting setpoints in upstream systems based on actual demand from downstream equipment. T&R can be used to reset any setpoint, but it is most often used to reset supply temperature and static pressure setpoints in air or hydronic distribution systems. It is commonly used to reset setpoints at AHUs based on demand at VAV zones or to reset chilled water (CHW) and heating hot water (HHW) plant setpoints based on demand from coils.

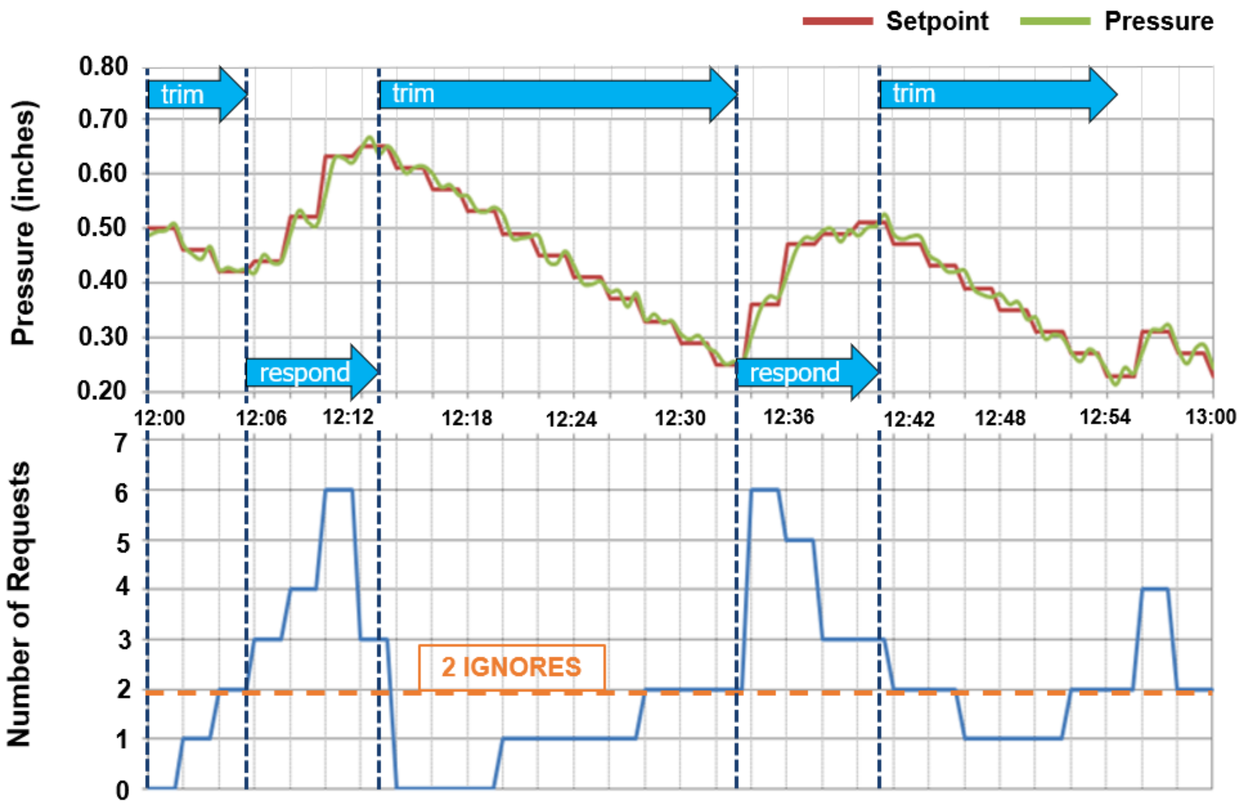


Figure 9. Example of Trim & Respond Control

T&R is one of the principal energy savings strategies used in G36. (Taylor, 2015) A T&R reset loop saves energy by slowly but continuously *trimming* the setpoint in the direction of lower energy use (i.e., raising a cooling setpoint or lowering a heating setpoint). This continues until the T&R loop detects demand from downstream (load serving) equipment, at which point it responds by resetting the setpoint in the opposite direction (e.g., colder cooling or warmer heating) to satisfy the unmet demand. The result is the setpoint slowly and gently oscillating around its ideal value, and this oscillation is normal and expected. Figure 9 illustrates how the changing number of requests causes the long-period oscillations typical of a T&R loop.

T&R determines demand based on requests that are generated by downstream equipment when they are unable to meet load. The BAS adds up the requests from each piece of upstream equipment; when they exceed a user-defined threshold, the system responds.

> The zone request totals can be useful to the operator, to understand the distribution of demand across a number of zones or coils and should be exposed by the BAS user interface (See Section 4.4). They are particularly useful for tracking down "rogue zones" – zones that continuously drive the T&R loop and prevent the reset from working (See Section 4.5.5).

It is important to note that T&R loops are almost never used to control equipment directly (e.g., fan speed, valve position). Most often, the T&R loop is used to reset the setpoint for a controlled value. Then a separate control loop (usually a traditional proportional integral [PI] loop) controls the equipment to maintain the value at the setpoint. This two-loop control strategy is common throughout

G36. Among other advantages, it permits the setpoint-reset loop and the equipment control loop to have different gains, so that the setpoint can change gradually, but the equipment can react to setpoints changes quickly.

The General section of the Guideline does not describe any specific applications of T&R, but instead describes the programming and parameters that define a T&R reset scheme. Specific setpoint resets are defined in the equipment-specific control sequences later in the Guideline. The Guideline itself includes a more detailed explanation as well as a worked example of the math underlying the T&R reset loop. Practitioners who are unfamiliar with T&R are encouraged to review this section.

Though many different strategies have been used for setpoint resets, T&R has generally emerged as the most common and successful approach, in part for its effectiveness, stability, and ease of tuning. For duct static pressure reset, an alternative setpoint reset approach is to use a proportional–integral–derivative (PID) control loop to maintain the most-open damper position at nearly fully open. Challenges with this strategy are tuning the PID loop, the inability to respond faster or slower as there are varying numbers of starved dampers, and the inability to tune the reset to delay response until a minimum threshold of zones are demanding additional pressure.

Table 5.1.14.3 Trim & Respond Variables

Variable	Definition
Device	Associated device (e.g., fan, pump)
SP0	Initial setpoint
SPmin	Minimum setpoint
SPmax	Maximum setpoint
Td	Delay timer
T	Time step
I	Number of ignored requests
R	Number of requests from zones/systems
SPtrim	Trim amount
SPres	Respond amount (must be opposite in sign to SPtrim)
SPres-max	Maximum response per time interval (must be same sign as SPres)

Informative Note: The number of ignored requests (I) should be set to zero for critical zones or air handlers.

The default parameters in G36 have generally been found to provide stable operation for typical office occupancy but stability may be specific to each application and tuning or adjustments may be required for some installations. A description of the key parameters and considerations for tuning adjustments is summarized in the Trim & Respond sidebar.

In addition to the main T&R parameters, another key parameter is the **Importance Multiplier** (**IM**) for each downstream zone or system. For each zone, the IM is set to a default of one, which generally equates to every zone or system having an equal vote in the setpoint reset. For zones that are more critical for meeting demand, the IM can be increased so that the T&R reset is more responsive to those zones. For non-critical zones where setpoint excursions can be tolerated, the IM can be set to zero to continually suppress requests from being considered in the T&R logic.

Trim & Respond Parameters

- **Device:** The **device** is the associated equipment whose operating status triggers the reset loop to be enabled or disabled.
- **SP0:** The **initial setpoint** is the value of the setpoint when the device and loop first become active. After the loop is started, the setpoint remains at SP0 for a time delay equal to Td, to allow the system to stabilize. As there is a delay in how long a setpoint can reset up or down, the selection of SP0 may be important to provide an appropriate starting setpoint during the initial operation at the start of each day. For example, the G36 default for the SAT reset is to start with SP0 equal to SPmax to delay the need for mechanical cooling based on the assumption that cooling loads are relatively low at system start up.
- **SPmin:** The **minimum setpoint** is the lower limit of the setpoint reset range. For SAT reset, this is generally set equal to the design temperature and need not be changed. For duct static pressure reset, this limit is defaulted to 0.1 inches. Though this pressure is generally lower than what could potentially satisfy zone airflow demands, there is no risk with keeping this value low. As the setpoint resets downward during periods of low demand, the associated zones will eventually generate requests if there is insufficient pressure, causing the setpoint to rise back up. In contrast, setting SPmin unnecessarily high (a common instinct for many installers) may lead to excess fan energy consumption when the minimum pressure is higher than demanded by the zones.
- **SPmax:** The **maximum setpoint** is the upper limit of the setpoint reset range. For SAT reset, this is often set to 65ºF for office buildings and sometimes higher for healthcare and laboratory buildings that have high minimum airflow requirements. Though increasing the value of SPmax may reduce cooling energy consumption during periods of low demand, there is a tradeoff with fan energy to consider: to satisfy the same cooling load, more airflow and fan power are required at higher SATs than at lower SATs, and the increase in fan energy can often exceed the mechanical cooling savings. For duct static pressure reset, SPmax is generally determined with the TAB contractor as the pressure that delivers the design airflow, with nearby dampers closed as needed, to achieve the diversified design airflow. Occasionally, higher pressures will be required to satisfy demanding zones. In theory, increasing SPmax should not have negative consequences, as the setpoint should only rise as far as needed to satisfy associated zones. In practice, setting SPmax too high can lead to a large increase in fan energy if there are rogue zones that continuously drive the setpoint to the upper limit.
- **Td:** The **time delay** during which the setpoint is held constant at SP0 when the reset loop is first enabled. This time delay is intended to allow the system to stabilize at start up before allowing the setpoint to reset.
- **T:** The **time step** for the setpoint reset. Generally, set to two minutes by default, the output of the T&R loop will remain constant during each time step to allow the control loop to catch up before the setpoint is reset up or down again.
- **I:** The **number of ignored requests** is the minimum threshold of requests that are required before the setpoint can respond to demand from associated equipment. For the airside T&R sequences, the number of ignores is set to a default of two, meaning that the setpoints will not begin to respond to zone demand until there are more than two zones generating requests. For small systems or critical applications, consider reducing the number of ignores to zero. For larger systems or where energy conservation is prioritized over strict temperature or airflow control, consider increasing the number of ignores.

- **R:** The **number of requests** is dynamically calculated as the sum of requests generated by associated equipment.
- **SPtrim:** The **trim amount** is the setpoint reset that occurs at each time step when the number of requests is less than or equal to the number of ignores. The trim is the reset in the direction of lower demand (e.g., higher SAT or lower duct static pressure setpoints). Note the sign of the trim amount. Setting the trim amount higher in magnitude will increase the speed at which the setpoint can reset in the direction toward energy conservation, but potentially at the cost of stability in the setpoint reset. If a reset loop is unstable (e.g., cycling repeatedly from the minimum to the maximum limits of the reset range in the shortest amount of time possible), the trim amount should generally be adjusted to be smaller in magnitude (closer to zero) to slow down the cycling in one direction. It is preferable to adjust the trim amount to slow down an unstable reset, rather than the respond amount so that the setpoint reset can be more responsive to rapid changes in demand.
- **SPres:** The **respond amount** is the multiplier that determines the setpoint reset that occurs each time the number of requests exceeds the number of ignores. The reset amount at each time step is SPres * (R – I) but no more than SPres-max. When there are few requests, the setpoint can reset slowly; when there are more requests, the setpoint can reset more quickly to meet demand. The respond amount must be opposite in sign to the trim amount. The respond amount is generally set greater and unequal in magnitude to the trim amount to be more responsive to changes in demand and naturally force the reset to continue to perturbed in order to seek out the optimal setpoint.
- **SPres-max:** The **maximum response per time interval** is a limit to prevent drastic swings in setpoint when there are many requests. This limit can be adjusted to increase reset responsiveness to rapid increases in demand, but potentially at the cost of stability in the

3.3 Generic Zones and Zone Groups

The next three sections: “Generic Ventilation Zones”, “Generic Thermal Zones” and “Zone Groups”, introduce concepts and logic that apply to every zone in the project, whether the zone is served by a single-zone AHU, any kind of terminal unit, or other means of controlling comfort and ventilation.

Note that, in the context of a VAV system, each zone is typically both a thermal zone and a ventilation zone, with identical boundaries. G36 has separated the two concepts to facilitate future support for other system types (e.g., radiant floors, or variable refrigerant flow systems + dedicated outside air systems) where the two types of zones may be distinct.

3.3.1 Generic Ventilation Zones

A ventilation zone is a space or group of spaces served by one ventilation control device (e.g., a VAV box) and which has specified values for minimum primary airflow and minimum outdoor airflow (either or both of which may be zero).

This section describes how the zone primary airflow setpoint is determined, how the zone minimum outdoor air requirement is calculated, and how both values are reset based on occupancy and CO_2 sensors and window switches, where applicable.

This section also contains the first major choice-point, which specifies whether outdoor air and ventilation requirements are calculated in accordance with California Title 24 or ASHRAE Standard 62.1.

Complete logic is provided for both methods, so the designer should choose one and provide the appropriate information to support it. (Title 24 requires the zone minimum and design outside air for each zone, whereas Standard 62.1 requires the area and population component of the breathing zone outdoor air requirement, Vbz-A and Vbz-P, respectively). Note that each option also includes additional minor choice-points embedded within it, because single-zone systems calculate ventilation differently than multiple-zone VAV systems.

This section also introduces the concept of Time-Averaged Ventilation, which enables a terminal unit to effectively maintain an airflow setpoint that is lower than its controllable minimum. It does this by alternately maintaining airflow at the controllable minimum and shutting off airflow entirely, so the zone receives the correct amount of ventilation, on average, over a period of an hour. This saves energy and avoids overcooling of cooling-only zones by supporting very low airflows while in deadband.

3.3.2 Generic Thermal Zones

A thermal zone—also called an “HVAC Zone” in Standard 90.1—is a space or group of spaces that has specified heating and/or cooling setpoints, a means to measure space temperature (e.g., a thermostat), and a device for controlling space temperature (such as a VAV box, fan coil unit, or hydronic manifold).

A generic thermal zone is required to support separate, independently adjustable, and non-overlapping setpoints for heating and cooling both while occupied and unoccupied—a total of four setpoints. These setpoints can be affected by occupant adjustments, demand-response load shed events, window switches, and occupancy sensors. Not all zones will have all these features, but a common set of zone control logic means that the software to support these features should be present in every zone controller, even if they are not enabled in every zone. This gives the owner more space-use flexibility by making it easy to add these sensors in later retrofits.

A generic thermal zone is also required to have two **separate and independent** PI zone temperature control loops, one for heating and one for cooling. The use of two distinct loops (rather than a single loop, as is historically common practice) is important because the value of these loops is often used in zone control logic, to generate T&R Requests, and more.

3.3.3 Zone Groups and Zone Modes

This section introduces the concept of Zone Groups, also called “isolation areas” in ASHRAE Standard 90.1. A Zone Group is simply a group of zones that all operate on the same occupancy schedule and are served by the same equipment. The division of the building into Zone Groups is a key energy conservation opportunity, as it allows for different portions of a building to be conditioned and ventilated on separate schedules, rather than conditioning an entire building based on a portion that has the longest operating schedule.

This section also introduces the concept of zone Modes, which include Occupied and Unoccupied as well as Setup/Setback and Warmup/Cooldown. Occupied Mode is triggered by a time-based schedule, whereas the other modes are triggered by zone temperature during the zone’s scheduled Unoccupied period. When any zone in a group enters a Mode other than Unoccupied, all the zones in the group enter that Mode. This ensures that there is sufficient load for equipment to run stably during after-hours operation, provided that the Zone Groups—which are designated by the specifying engineer—are large enough.

Warmup and Cooldown modes are triggered by optimal-start logic (a standard block in most BAS products), wherein the BAS automatically calculates how long in advance of scheduled occupancy the system needs to start to achieve Occupied setpoint by the appointed time. These modes save energy compared to simply starting a zone hours before occupancy, as they improve the efficiency of pre-heating and pre-cooling by operating with outdoor air set to zero (unless economizer cooling is available) and zone supply airflows at their maximum value (as acoustics is not a concern during this period). See Section 3.5.4 for more information.

It is important to note that **the Occupied period should be scheduled to begin at the actual start of occupancy, rather than some hours before**—the optimal-start logic ensures that the building will be comfortable when the occupants arrive.

3.4 Terminal Unit Control Logic

Subsequent sections of Part 5 provide control logic for a number of different terminal unit types and control strategies. What follows is a review of some key concepts that are shared among all terminal unit control sequences, as well as discussion of logic for specific terminal types.

3.4.1 Airflow Setpoints

For all types of terminal units, the sequences reference "Generic Ventilation Zones" to determine the minimum outdoor air and zone supply airflow setpoints and "Generic Thermal Zones" for zone temperature control logic. Zone temperature and design airflow setpoints are provided in Part 3, which may in turn refer to mechanical schedules.

Every terminal unit has at least two airflow setpoints (minimum **Vmin** and cooling maximum **Vcool-max**); some have additional minimum and maximum airflow setpoints for heating, **Vheat-min** and **Vheat-max**. Significantly, these setpoints are the ones that apply during Occupied Mode operation.

A common feature that appears in every zone sequence is a table called "Endpoints as a Function of Zone Group Mode". This example is for a VAV-reheat terminal unit:

Endpoint	Occupied	Cooldown	Setup	Warmup	Setback	Unoccupied
Cooling maximum	Vcool-max	Vcool-max	Vcool-max	0	0	0
Cooling minimum	Vmin*	0	0	0	0	0
Minimum	Vmin*	0	0	0	0	0
Heating minimum	Max (Vheat-min, Vmin*)	Vheat-min	0	Vheat-max	Vheat-max	0
Heating maximum	Max (Vheat-max, Vmin*)	Vheat-max	0	Vcool-max	Vcool-max	0

Endpoints refer to the variable used in the control logic diagrams and the associated sequences. This table establishes how the airflow endpoints are applied when a zone is in various Modes. In nonoccupied modes, zone minimum airflows are set to zero to avoid supplying any air in the deadband since ventilation is not required (though it is not shown here, the outdoor air requirement at the AHU is also set to zero for this reason). Heating effectiveness in Warmup and Setback is further maximized by allowing the airflow to reset up to the (higher) design cooling maximum airflow while providing supply air at a typical heating temperature. The table from G36 is represented graphically in Figure 10 below.

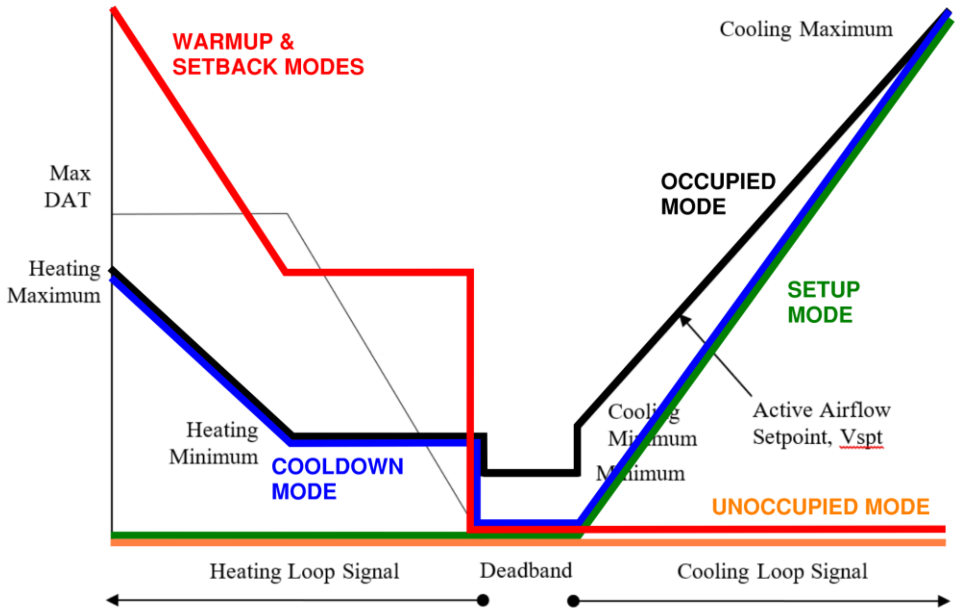


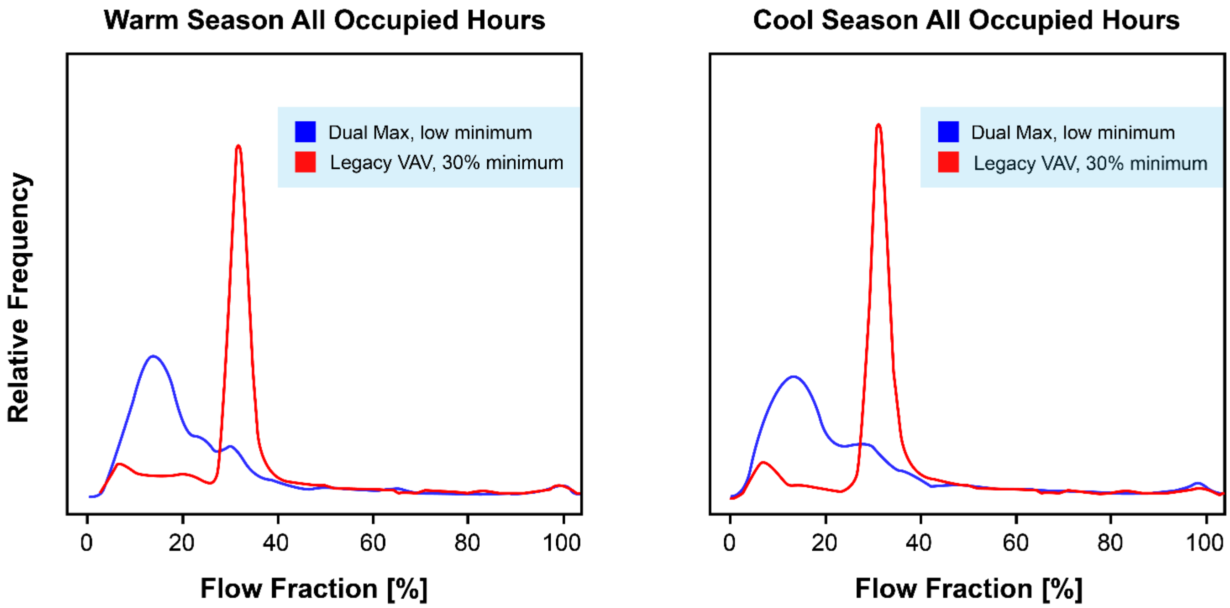
Figure 10. Airflow Setpoints in Different Operating Modes in Guideline 36

Also note the use of **Vmin***. As discussed above, **Vmin*** represents the currently applicable occupied minimum airflow setpoint. It is usually equal to the minimum airflow **Vmin**, but it may be reset based on CO_2 or occupancy sensor input, as described in Section 3.3.1. (Note that in the 2018 version of G36, **Vmin** is a scheduled value provided on drawings; however, starting with the 2021 version it may be automatically calculated based on zone outdoor air requirements.)

3.4.2 Zone Minimum Airflow

The zone minimum is the airflow provided when a zone is in deadband mode. Conventional practice is to set this rate equal to a fixed percentage of the zone design flow, between 20 to 50% of the design cooling maximum flow. This setpoint must generally be non-zero to provide minimum ventilation to occupied spaces, but it is often set higher than minimum ventilation due to concern over VAV box controllable minimums and lack of awareness of the importance of this setpoint.

The energy and comfort benefits of low minimums are well supported by research. (Arens, et al., 2015; Paliaga, Zhang, Hoyt, & Arens, 2019) ASHRAE research project RP-1515 compared the energy and thermal comfort performance between conventional 30% zone minimums and dual maximum VAV logic with low minimums. Figure 11 below shows that typical office building loads require zone airflows that are far below 30% of the cooling maximum. In the baseline case, in both warm and cool seasons, the frequency plots show that the zones spend the vast majority of their time at the minimum limit of 30%. When the zone minimum is reduced, the zones are able to operate at much lower airflows and still satisfy zone heating and cooling needs. Also noteworthy is how infrequently the zones operated above 40 to 50% of the design airflow. Figure 12 below shows the fan power measurements as a function of outdoor air temperature for the two zone airflow control strategies, showing that the dual-maximum approach with low minimums consistently saves energy across all operating conditions. The lower minimums not only reduce fan power, but also result in reductions in system cooling and reheat energy. Overall HVAC savings from reducing the zone minimum airflows ranged from 10 to 30% at the study buildings in RP-1515. (Arens, et al., 2015) Reducing zone minimum airflow is a central energy savings strategy for the G36 sequences.



(Arens, et al., 2015)

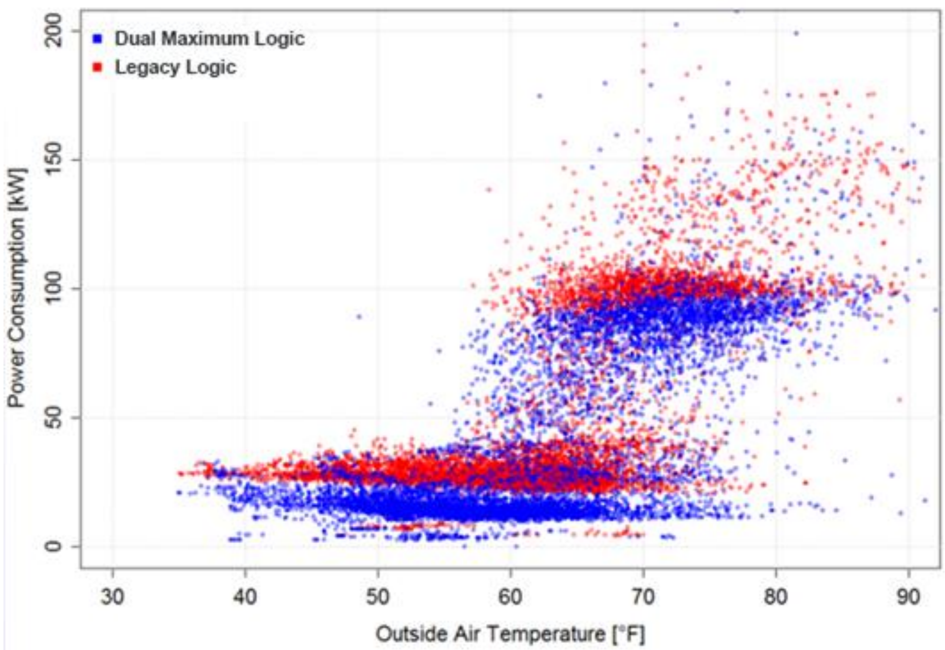
Figure 11. Measured Zone Airflow Fractions for Dual Maximum vs Legacy VAV Logic

To actually achieve these benefits, the specifying engineer must set zone minimums accordingly. Ideally, they will calculate the minimum airflow at each zone based on actual area and expected occupancy, rather than as a fixed percentage of the design cooling airflow as has been typical historical practice.

> If upon reviewing the zone schedule, the controls installer (or commissioning provider!) finds that the zone airflow minimums are consistently more than 20% of the design maximum, they should issue an RFI and ask the designer to consider lower minimums. This is particularly true if each zone's minimum is the same percentage of design airflow, which suggests that the designer did not evaluate minimum airflow requirements individually for each zone.

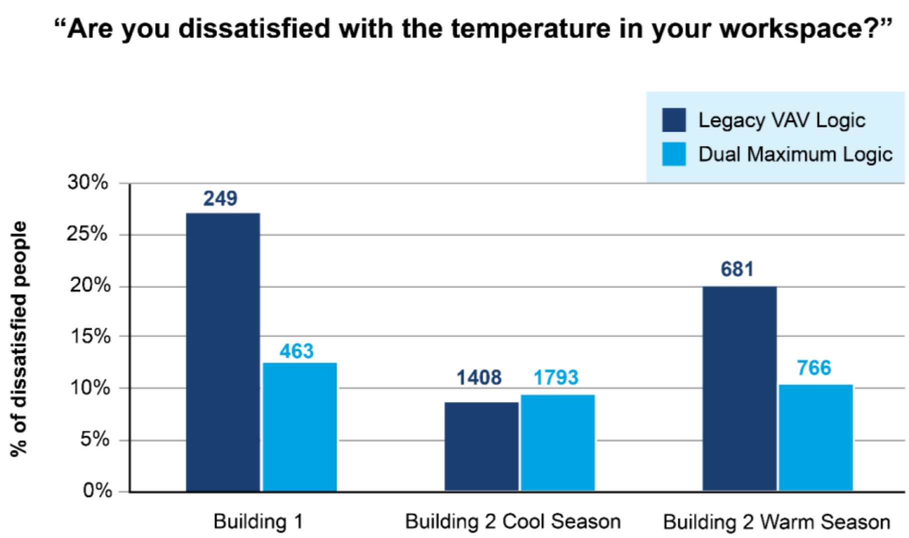
Current versions of ASHRAE Standard 90.1 and Title 24 require the minimum airflow in deadband to be no larger than the ventilation requirement (with some exceptions).

The higher-than-necessary zone airflows in the 30% baseline, represented in Figure 11, often results in the overcooling of spaces, even in the cooling season and in zones with reheat. RP-1515 evaluated occupant satisfaction in the baseline and low minimum cases and found higher rates of occupant dissatisfaction in the baseline case, particularly in the warm season (shown in Figure 13 below). As typical building internal loads decrease with more efficient lighting and computer equipment, conventional zone minimum airflows in deadband exceed the typical cooling requirement, causing spaces to be overcooled. In spaces with reheat, zone temperatures are often driven downward to the heating setpoint, and worse in spaces without reheat, even in the warm season. These temperatures fall below typical comfort ranges for office spaces in the warm season where occupants may be wearing lighter clothing.



(Arens, et al., 2015)

Figure 12. Fan Power Consumption for Dual Maximum vs Legacy VAV Logic



(Arens, et al., 2015)

Figure 13. Occupant Satisfaction Survey Results

3.4.3 Controllable Minimums

A VAV box controllable minimum is the lowest possible VAV box airflow setpoint (other than zero) that can be stably and accurately controlled. Stability is important for equipment operational performance and longevity; accuracy at low flows is important for ensuring that minimum ventilation requirements are met. Though most VAV box manufacturers publish tables of controllable minimums as a function of box size, they are generally conservative as the VAV box manufacturers do not have all of the information needed to determine these limits. This is because the controllable minimum depends on two main components: the flow probe, provided by the box manufacturer, and the zone controller/pressure transducer, which is typically provided by the controls manufacturer—a separate company. In most construction projects, the designer does not know during design which manufacturer's VAV boxes or VAV box controllers will eventually be installed; therefore, they generally cannot determine the controllable minimum during the design stage. Nevertheless, previous studies have shown the importance of setting VAV box minimum airflows as low as possible. Research by Pacific Gas and Electric Company (PG&E) of various combinations of VAV boxes and controllers found that minimum airflow setpoints of 10% of design flow were stable and accurate, and high accuracy could be achieved down to velocity pressures as low as 0.003 inches of water. (Dickerhoff & Stein, 2007)

If the VAV box controller can control to 0.004 inches, one option is to set the controllable minimum for the listed box manufacturer based on the values in Table 3 below. These values were determined based on the procedures outlined in G36 and with flow pickup amplification factors published by the VAV box manufacturers.

Table 3. VAV Box Controllable Minimums

Inlet Size (in)	Titus	Krueger	Price	MetalAire High Gain	ETI
4	15	15	20	15	15
6	30	35	30	30	30
8	55	60	55	50	55
10	90	90	95	85	90
12	120	130	135	110	130
14	190	175	195	155	180
16	245	230	260	210	235
24x16	455	445	490	N/A	415

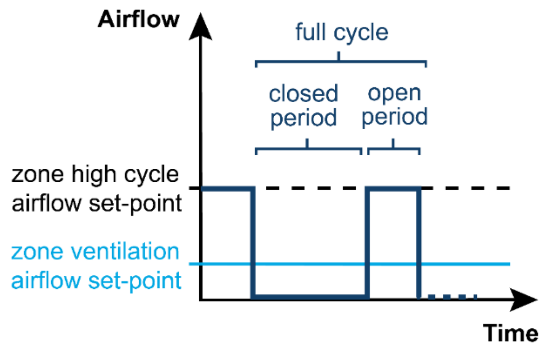
Taylor Engineers

Alternatively, G36 addresses this by outlining the calculation methodology and deferring the determination of the controllable minimum (Vm) to the controls installer, since the box and controller manufacturers should be known at that point. See Section 3.3 in the 2021 version of G36 for more information.

3.4.4 Time-Averaged Ventilation

In some situations, the controllable minimum for a particular zone may exceed the minimum ventilation required. Time-averaged ventilation (TAV) is a control strategy that allows a VAV box to effectively operate at less than its controllable minimum airflow. (Kaam, Raftery, Cheng, & Paliaga, 2017) TAV alternates the VAV damper between partially open and fully closed so that the average airflow matches the minimum ventilation requirement (shown in Figure 14 below). This is acceptable under ASHRAE Standard 62.1 and California Title 24, as both codes allow for ventilation requirements to be met based on the average airflow over a period of time.

During the *open period*, the zone airflow can be set to the controllable minimum or higher to ensure stable and accurate flow control. During the *closed period*, the VAV damper is fully closed avoiding any issues with flow measurement and control stability. The ratio of the duration between the open and closed periods is calculated by the relative ratio of the airflow setpoint in the open period and the minimum ventilation requirement. This time-averaging method may reduce energy use and the risk of overcooling when the zone ventilation requirement is less than the VAV box controllable minimum.



(Kaam, Raftery, Cheng, & Paliaga, 2017)

Figure 14. Illustration of Time-Averaged Ventilation

3.4.5 Dual Maximum VAV Control Logic

For VAV boxes with reheat coils, G36 provides so-called *dual max* control logic.

This name can be understood in contrast to historical practice, i.e., *single max* VAV, wherein there is only a single (cooling) maximum airflow setpoint and a minimum airflow that is often set to deliver design heating capacity. The high minimum flow with single max VAV control can lead to significant energy waste and occupant discomfort, as described in Section 3.4.2.

Dual max VAV logic addresses this problem by establishing separate heating airflow and minimum airflow setpoints. The zone airflow is reduced to only provide minimum ventilation in deadband mode to minimize excess reheat, and then rises to a higher heating maximum airflow to provide sufficient heating capacity when needed. **Dual maximum VAV logic is a prescriptive requirement in Standard 90.1 and Title 24.** Figure 15 below illustrates the differences between the two control strategies.

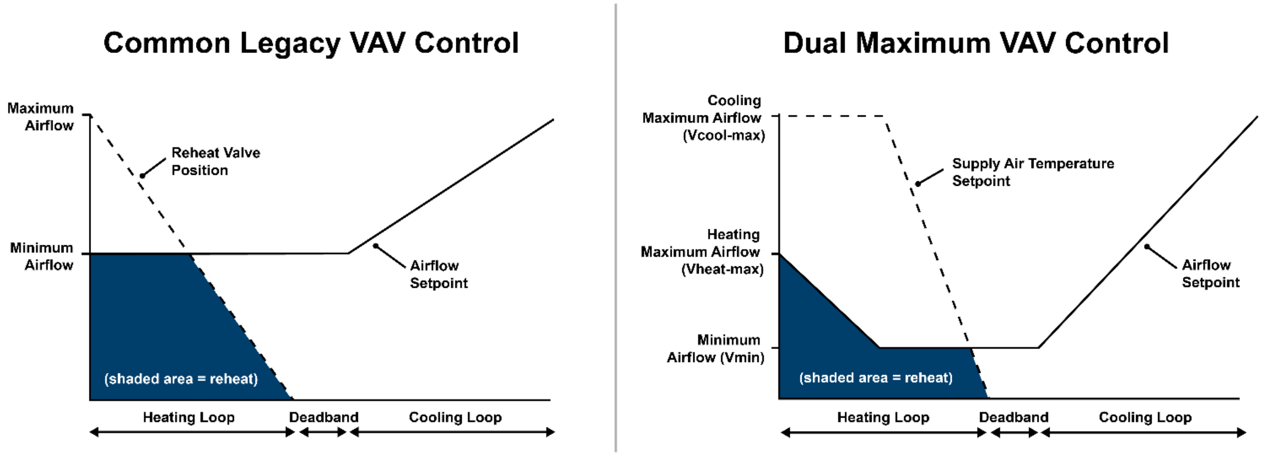
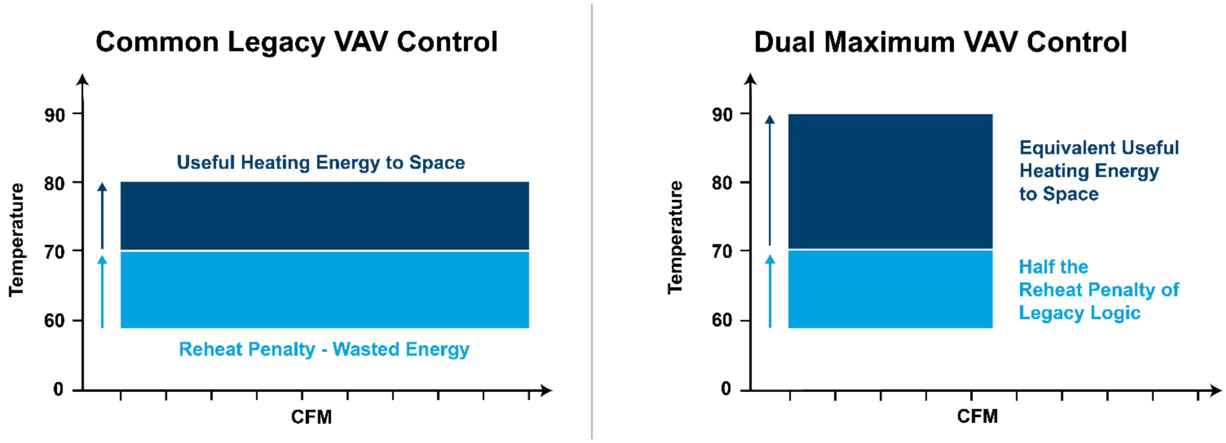


Figure 15. Conventional vs Dual Maximum VAV Logic

Rather than modulating the reheat directly based on the zone heating loop output as in common practice, dual max control resets a zone discharge air temperature (DAT) setpoint and then modulates the heating coil output to maintain the DAT at setpoint. The DAT setpoint is generally limited to 90°F (20°F above ambient room temperature) to prevent excessive stratification in heating mode. The buoyancy of hotter DATs prevents the hot air from mixing into the space, causing the hot air to bypass directly to the return grilles (for ceiling supply, ceiling return systems) and reducing the effective heating capacity of the systems.

Dual max logic requires the designer to specify the design cooling airflow setpoint (Vcool-max), the minimum airflow setpoint (Vmin), and the design heating maximum airflow setpoint (Vheat-max). Alternatively, G36 allows the designer to set Vmin to AUTO and instead require the BAS to determine Vmin dynamically. An optional heating minimum setpoint (Vheat-min) is also supported for devices with a minimum heating flow requirement such as electric resistance coils.

The heating loop control signal is used to first reset the DAT setpoint and then secondly to reset the primary airflow setpoint. This strategy saves energy in two ways. Using a separate **Vheat-max** allows the zone minimum to be reduced to the ventilation minimum in deadband, which saves energy and improves comfort as discussed in the previous section. In addition, sequencing the DAT reset and then the airflow reset reduces the reheat penalty under off-peak conditions. The reheat penalty is the energy used to reheat the air from the SAT (typically 55 to 65°F) to room ambient (~70°F), before heating the air above ambient to provide heat to the space. This portion of the reheat is pure wasted energy from a comfort cooling point of view, as it merely cancels out AHU cooling and does not contribute to meeting the space heating loads.



To deliver the same amount of heating to a space (area shaded in dark blue), dual maximum VAV control incurs a lower reheat penalty (light blue area) compared to the common practice. Energy use is proportional to temperature rise times airflow.

Figure 16. Dual Max Logic Incurs Less Reheat Penalty

As Figure 16 above illustrates, a high minimum airflow in a reheat zone implicates a large reheat penalty. Under part-load conditions, such a zone will meet load by heating a large volume of air to a moderately warm temperature (shown as 80°F in the figure). Conversely, a zone with dual max logic will meet that same load with less airflow at a higher DAT (limited by the maximum permitted ΔT relative to the zone setpoint), thus incurring less reheat penalty. Both types of logic will behave identically under design conditions—using the same amount of energy and ensuring that dual max logic can meet peak load as effectively as legacy logic. However, as most zones are well below design load the vast majority of the time, dual max logic (with well-chosen minimums) can significantly reduce energy use.

Besides common VAV boxes, G36 also provides control logic for less common terminal unit types, including fan-powered VAV boxes and dual-duct boxes. These devices inherently decouple the heating airflow from the cooling airflow, so dual-max logic is not required for these types of terminal units.

3.4.6 Occupied-Standby Mode

Ventilation is generally required to address indoor air pollutants from occupants and other building-related sources. The resulting minimum ventilation rates established by ASHRAE Standard 62.1 and California's Title 24 are thus based on people- and area-based requirements. In the past, minimum ventilation was required to be maintained during normal occupancy periods to control for area-based sources, even if there were no occupants in the space. The 2016 version of Standard 62.1 first introduced occupied-standby mode, which allows zone ventilation to be reduced to zero when a zone is sensed to be empty for most typical space types. **Standard 90.1-2019 prescriptively requires occupied-standby mode** for most enclosed spaces and where permitted by Standard 62.1. **Title 24-2019 has a mandatory requirement for occupied-standby**. Note that though Standard 62.1 is the basis for ventilation requirements across most of the country, and Standard 90.1 is the basis for energy performance for many states, there is often a multi-year delay from when new changes are first effective in the standards to when they become applicable codes, due largely to the timing of model code updates and subsequent adoption cycles of state and local codes.

Occupied-standby includes a zone setpoint reset, in addition to zeroing out the ventilation in unpopulated spaces. Standard 90.1 and Title 24 require the zone heating and cooling setpoints to be setback and setup by 1 to 2°F, and the zone airflow to be reduced to zero when a space is in deadband mode. With dynamic ventilation control at the AHU outdoor air intake, the system level outdoor airflow can also be reduced during periods of partial occupancy by the corresponding amount. A simulation study found that occupied-standby mode saved 20 to 40% of HVAC energy use across different U.S. climate zones for a prototype medium office building that was modified to include detailed thermal zones and stochastic occupancy profiles. (Pang, et al., 2020) Though heavily dependent on building occupancy schedules and other factors, occupied-standby mode is a simple and cost effective means to potentially achieve deep energy savings in partially occupied buildings. Note that the temperature setback required by building energy standards is relatively modest. The intent is to reset the setpoints just enough to allow the zone to enter deadband mode and reduce zone airflow to zero, without impacting comfort when the occupants return. Deeper setbacks have the risk of creating causing comfort complaints due to longer recovery times, which may lead to disabling the strategy altogether and creating critical zones that drive the system-level resets during recovery, which may outweigh or takeaway from the energy savings of occupied-standby mode. Accurately sensing occupancy is a critical issue—see Section 4.3.11 for a discussion on occupancy sensors.

3.5 Control of Multiple-Zone Air Handling Units

Guideline 36 provides two control logic sequences for AHUs that serve multiple zones.

Multiple-Zone VAV logic is the workhorse AHU logic that addresses most conventional single-duct VAV system designs. While a preheat coil in the AHU is supported, this logic is intended for a unit that primarily provides cold air and ventilation to terminal units. This logic is also used for the cold deck of a dual-fan, dual-duct AHU system.

Dual-Fan, Dual-Duct (DFDD) Heating VAV logic is a version of the previous sequence that has been simplified by removing the cooling and outdoor air ventilation/economizer control logic and associated fault detection. It addresses the hot deck of a DFDD AHU system, and it should be issued alongside the regular multiple-zone AHU logic for the cold deck.

It is very important to correctly associate each VAV box to its respective AHU.

These multiple-zone AHU logic sequences are designed to work with one or more of the G36 terminal unit sequences. These terminal unit sequences provide zone-level feedback to the AHU (mostly in the form of Requests) to enable demand-based resets of SAT, static pressure, and outdoor air fraction.

The correct mapping of each terminal unit/zone to its AHU is critically important for correct system operation. If there is more than one multiple-zone AHU in the project, the installer should verify that these relationships are clearly and unambiguously identified.

3.5.1 Demand-Based Setpoint Resets for Supply Duct Static Pressure and SAT

The AHU sequences use T&R logic (see Section 3.2.5) to reset the setpoints for both duct static pressure (which controls the fan speed) and SAT (which controls heating coil, cooling coil, and economizer dampers) based on zone demand. Since multiple zones are served, the goal is to provide enough air and enough cooling (or heating, in the case of the DFDD sequences) to meet the needs of the most demanding zone, but no more. VAV reheat systems are inherently inefficient: fans consume energy to generate pressure in the ductwork that is then “chewed up” by the VAV dampers to modulate airflow to the zones; cooling coils make cold air that is then reheated by the VAV reheat coils. This is akin to driving with one foot on the gas and one foot on the brakes. This waste is, in some ways necessary, in multiple zone systems to effectively be able to simultaneously serve varying thermal and ventilation requirements. However, smart control strategies and effective setpoint resets can minimize the energy waste to produce high-performance, low-energy VAV systems.

For duct static pressure control, the optimal operation is to control a fan to generate just enough pressure, so = all zone airflow setpoints are satisfied and the most-open damper is almost nearly wide open. More pressure would cause that most-open damper to be partly closed, which would waste fan energy. Less pressure would cause that most-open damper to fail to meet its airflow setpoint. The T&R setpoint reset aims to maintain that optimal pressure setpoint as the zone demands vary dynamically.

The optimal SAT setpoint control is a more complex balance, but the intent is to deliver sufficiently cold air to satisfy cooling demand (or sufficiently warm air to meet heating demand) but to otherwise reset the setpoint upward to maximize economizer cooling and minimize mechanical cooling. More on this in Section 3.5.2.

Duct static pressure and SAT reset are required by Standard 90.1 and Title 24.

At the zone level, the terminal unit sequences generate a request for more static pressure when the zone damper is nearly fully open and/or not meeting airflow setpoint, whereas a request for lower (or higher) SAT is generated based on the value of the zone’s cooling (or heating) control loops. This means that, in most cases, a zone will try to meet its load first by increasing airflow at the current SAT (for single-duct systems, this is true only of cooling; for DFDD AHUs, this logic applies to both cooling and heating airflows). If the available duct static pressure is not sufficient to meet the zone airflow setpoint, the zone will request additional static pressure. Only if the additional airflow is not sufficient to meet load (or not available due to system limitations) will the zone then request colder (or warmer) air from the AHU.

The static pressure setpoint and the supply air temperature setpoint are reset independently by separate loops.

Sequencing the resets in this fashion also allows the zones to adapt to changes occurring at the system or plant level. If the SAT decreases as a result of AHU control logic or changing outdoor conditions, zones with a cooling demand will reduce their airflow, enabling the T&R loop that controls the AHU’s static pressure to find a lower setpoint that will still satisfy the zones.

3.5.2 Cooling Supply Air Temperature Setpoint Dual-Reset Strategy

All VAV AHUs face a fundamental tradeoff between cooling energy and fan energy. The total cooling required is determined by the most demanding zone, but within limits that load can be met by reducing SAT or by increasing airflow to find the most efficient operating point.

G36 addresses this with a **two-factor SAT reset based on cooling demand and outside air temperature (OAT)**. When the OAT is low, it maximizes free cooling by keeping the SAT setpoint as high as possible while still meeting zone demand. As the OAT rises and economizer cooling is less favorable, the SAT setpoint is reduced. Under off-peak conditions, a lower SAT setpoint reduces the airflow required to meet load, allowing the static pressure reset loop to reduce fan speed and save fan energy per the cube law.

Figure 17 below shows the reset diagrammatically for OAT and SAT limits typical of office buildings. OAT and SAT endpoints can be adjusted for other applications.

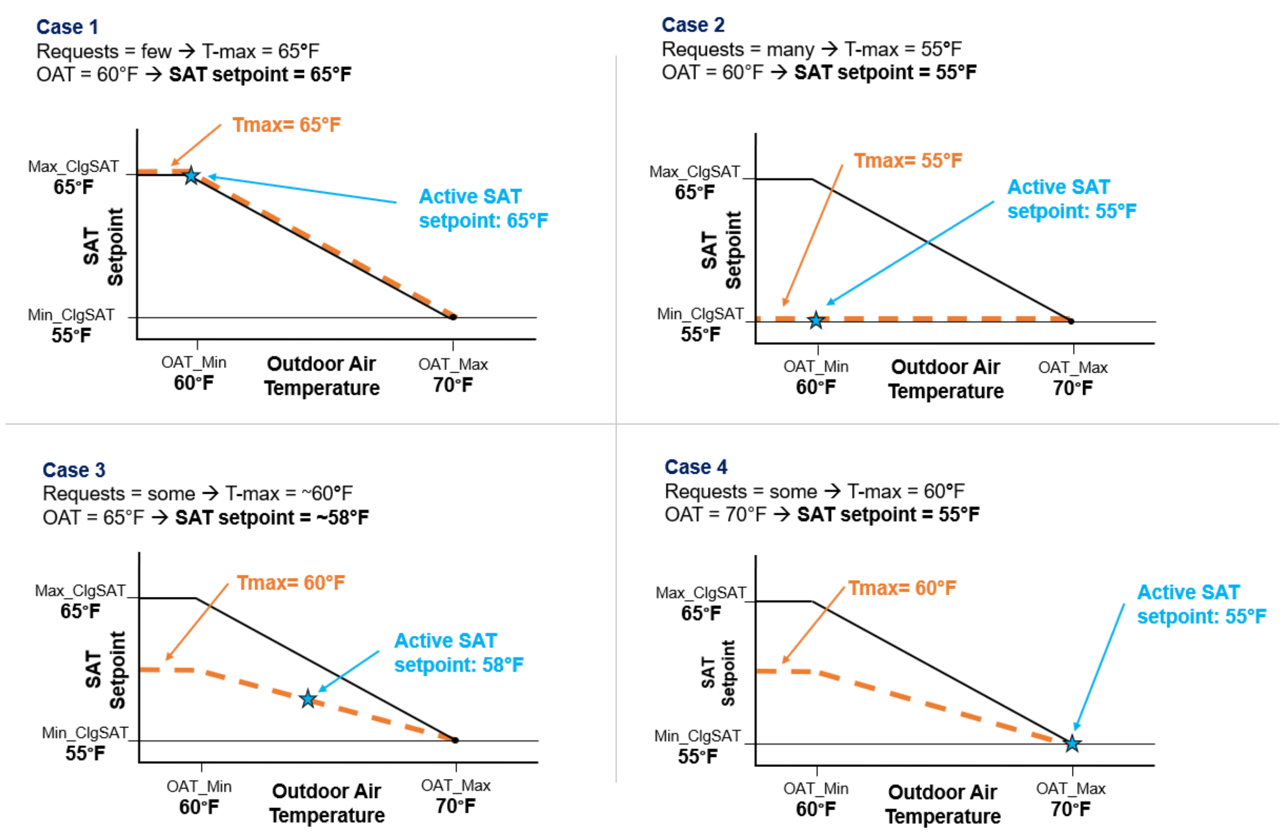


Figure 17. Examples of SAT Reset by Demand and OAT

The value of T-Max (dashed line) is reset between the minimum and maximum cooling SAT setpoints (determined by the designer) based on demand (i.e., SAT reset requests from zones). This ensures that all zones can get sufficiently cold air. The SAT setpoint is subsequently determined by a proportional linear reset based on OAT. This prevents the system from wasting fan energy by trying to cool with a too-high SAT.

It is important to remember that G36 resets the static pressure setpoint and the SAT setpoint independently, using entirely separate loops. Both setpoints react to zone demand, but each uses a distinct type of request: *cooling SAT reset requests* and *static pressure reset requests* are generated by different conditions at the zone, and they are totaled up separately at the AHU. This allows the system to adjust dynamically to changes in both outdoor and zone conditions. Although it is not a full optimization solution—it does not consider the project-specific cooling plant or fan efficiency—it helps balance fan energy vs compressor energy to avoid wasteful extremes.

3.5.3 Supply Air Temperature Control

Once the system has determined the current SAT setpoint, a control loop operates the AHU to maintain the SAT at setpoint. This control loop sequences the preheat coil (if present), then the economizer dampers, and finally the cooling coil, based on the output of the SAT control loop (i.e., error between SAT and setpoint).

This diagram represents the logic for an AHU with a relief fan (return fan AHUs are slightly different):

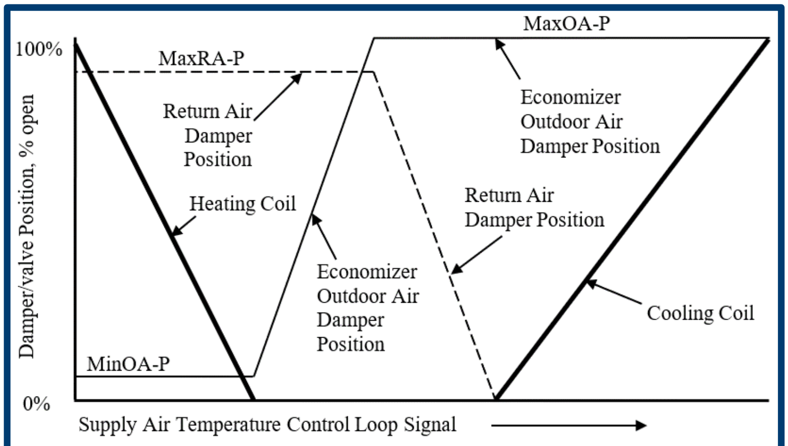


Figure 5.16.2.3-1 SAT loop mapping with relief damper or relief fan.

A single loop is used to control all three functions, because doing so makes simultaneous heating and cooling—a common cause of wasted energy[2]—nearly impossible. This approach also avoids the common practice of controlling the economizer based on mixed air temperature (MAT), where differential error between the SAT and MAT sensors may lead to simultaneous heating and cooling or engage the mechanical cooling before the economizer is fully maximized.

3.5.4 Optimum Start and Morning Warmup and Cooldown

One of the simplest and most effective building energy conservation measures is to simply reduce the HVAC system run time. Optimum start is a control strategy that has existed for decades but is implemented in surprisingly few buildings. When systems are scheduled off at night, often they need to be operated for some amount of time prior to the start of occupancy to recover from temperature

[2] G36 does not include humidity control logic; it must be programmed on an ad-hoc basis if required. For dehumidification, the cooling coil must be upstream of the heating coil and have a separate coil-leaving temperature sensor. During dehumidification, the cooling coil is controlled by its coil leaving temperature (CLT) sensor while the heating coil is controlled by the SAT control loop (and the economizer is fixed at minimum by OAT lockout). Under normal operation, the most-downstream sensor should be used to control all functions, and the upstream CLT sensor should be ignored.

setbacks at night. Rather than start the HVAC systems based on a fixed schedule where the start time is set conservatively early based on the most demanding recovery times, the intent of optimum start is to operate the systems for just as long as is necessary to recover space temperatures by the start of the occupied period. In very hot or very cold weather, optimum start would begin earlier to warm up or cool down the building, in mild weather, optimum start would be able to begin later—saving energy by reducing system runtime. Not just a good energy efficiency measure, **optimum start is a mandatory requirement** in Standard 90.1 and Title 24, except for systems that are required to operate continuously. Optimum start routines generally evaluate the difference between actual zone temperatures and occupied setpoints, OAT, the amount of time prior to the scheduled occupancy, and a mass or capacity factor that is specific to the building or each zone. The mass/capacity factor often must be learned by the BAS based on a tuning period or manually adjusted. G36 does not provide an explicit control sequence for optimum start as many BAS manufacturers have their own, sometimes proprietary, algorithms.

When initiated, optimum start triggers the system to operate in either Warmup Mode to raise space temperatures up to the Occupied Mode heating setpoints or in Cooldown Mode to lower space temperatures down to the Occupied Mode cooling setpoints. This is a key point: Warmup and Cooldown Modes occur when a building is unoccupied, so ventilation requirements are not applicable. Warmup Mode operates in full recirculation mode to avoid the energy waste of having to unnecessarily preheat cold outdoor air and to reduce the recovery time, and zone heating airflows modulate from the heating max (Vheat-max) up to the cooling max setpoints (Vcool-max). Minimum zone airflows are zero in Warmup and Cooldown mode. See Figure 10 for an illustration of zone airflows in the different operating modes.

3.5.5 Automatic Fault Detection and Diagnostics

G36 includes AFDD logic for air handling units, based on an approach developed by researchers at the National Institute of Standards and Technology. Faults are detected by a series of rules, largely based on intuitive thermodynamic relationships. For example, the MAT should be between the return air temperature (RAT) and the OAT; if not, something is wrong. Different rules are active depending on whether the unit is in heating, cooling, free cooling, etc. Active rules are evaluated continuously, providing real-time fault detection.

When a fault condition is detected, the system will suggest potential causes based on which of the thermodynamic rules was violated. Most individual faults have more than one possible diagnosis, but if multiple faults are detected simultaneously, then the underlying cause will likely be obvious because it appears multiple times.

To minimize false alarms, each of the rules has one or more factors to account for sensor error. The default values of these error factors are based on the NIST research, and they should be appropriate for most buildings. If the AFDD logic seems to be triggering inappropriately, these factors can be adjusted to make the system less sensitive.

3.6 Control of Single-Zone Air Handling Units

G36 also provides logic for a smaller AHU or package unit (which has programmable controls) that provides heating, cooling, and ventilation to a single zone. It shares many features with the multiple-zone AHU logic, but it uses a different approach for determining fan speed and SAT.

The single-zone VAV (SZVAV) logic measures zone demand directly via a single thermostat, so separate terminal unit logic is not required and should not be used with the single-zone sequences. Instead, the single-zone logic applies the control concepts of *generic ventilation zones* and *generic thermal zones*—determining outdoor air setpoint and zone temperature control loops—directly to the AHU.

A unit serving a single zone does not have to balance competing demands of multiple zones with independent needs for cooling, heating, and airflow. This allows the single-zone logic to reset the fan speed setpoint and the SAT setpoint simultaneously, directly from the output of the zone heating loop and cooling loop, rather than using two separate loops a the multiple-zone AHU logic does. Note, however, that while a single loop controls both setpoints, a separate loop controls the actual speed of the fan to meet its setpoint; likewise, separate loops control the coil valves to meet the SAT setpoint.

Starting from a deadband condition, as the zone heating demand increases, the AHU responds in the classic *dual-max* fashion to minimize reheat penalty. First, the SAT setpoint is increased while maintaining the same airflow (fan speed); if this is not sufficient to meet demand, fan speed is increased only after SAT reaches its maximum setpoint.

The cooling response is significantly more complex. As with multiple-zone AHUs, the sequences try to balance fan energy versus compressor energy and maximize the opportunity for free cooling. This is accomplished by a two-prong strategy:

1. Different setpoints are used to control the economizer (SAT_{SP}) and the cooling coil (SAT_{SP}-C). The economizer setpoint is reduced first, at a lower signal value from the zone cooling loop, while the cooling coil setpoint is reduced only when zone cooling demand reaches its maximum value. This effectively sequences the economizer response and the cooling coil response, with a significant gap between them.

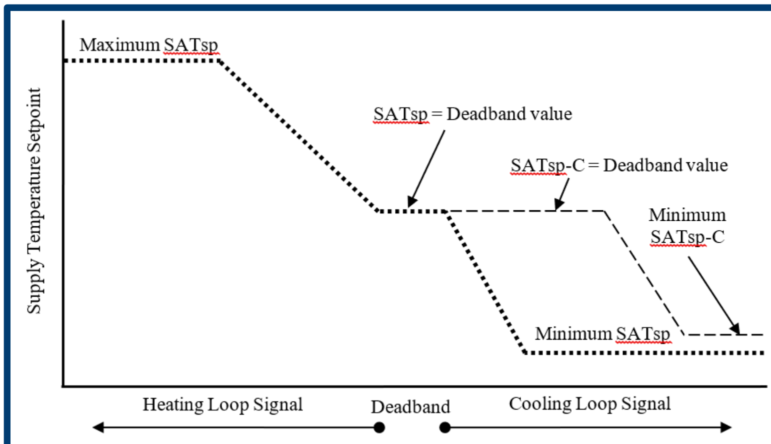


Figure 5.18.4.5-3 Control diagram for SZVAV AHU—supply air temperature.

2. The fan speed in cooling is reset differently depending on the outdoor air temperature. At a low OAT, the fan speed increases quickly with the zone cooling demand—this maximizes free cooling, and ideally meets the cooling load before the cooling coil is engaged. At high OAT, the

fan speed remains low until the cooling coil is engaged—this avoids wasting fan energy when free cooling is unavailable.

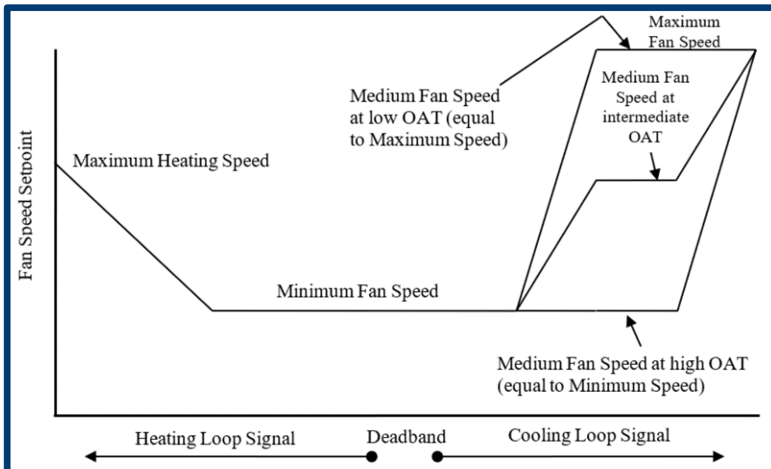


Figure 5.18.4.5-2 Control diagram for SZVAV AHU—fan speed.

Just as there are two distinct cooling SAT setpoints, there are separate SAT control loops. One of them sequences the heating coil (if any) and the economizer to meet SAT_{SP}, subject to limitations on minimum position (from the zone CO_2 control loop) and maximum position (from economizer OAT lockout). This resembles the control logic used for SAT control on multiple-zone AHUs, except without the cooling coil. The cooling coil is controlled by an entirely separate PI loop, to meet its own setpoint SAT_{SP}-C.

Modeling of a SZVAV system in a co-simulation between Modelica and EnergyPlus found that the G36 approach consumed 22% less HVAC energy in the Oakland, California climate (ASHRAE climate zone 3A, CA climate zone 3) compared to a baseline strategy. (Cheng, Singla, & Paliaga, 2022) Much of the savings were attributed to reduced cooling energy consumption with improved airside economizer performance; savings would likely be lower in climates with fewer hours of economizer potential.

4

Control System Best Practices

- BAS Product Selection and Bidding
- Setpoints
- Control Hardware and Sensors
- Graphics, Data Management, and User Interface
- Testing and Commissioning

4 Control System Best Practices

While good control sequences are critical, many other parts of the BAS must be correctly specified and installed for the BAS to perform well. In some cases, the sophistication of the G36 sequences requires greater-than-usual care around the specification of sensors, the provisioning of setpoints, or the testing of programmed sequences. In every case, adherence to best practices will maximize the chances of project success.

BASs are complex and heavily dependent on the details of its sensors and devices, as well as installation and configuration. **Do sweat the details.** Provide a detailed specification, scrutinize the submittals, and review the installation and operation closely. These efforts are necessary for a well-performing system with fewer compromises at the end of the project. BAS performance is critically dependent on having a robust network architecture, appropriately-accurate sensors that are located correctly, effective programming, diligent point mapping and calibration, etc. Small, overlooked details have to potential to have a strong negative impact on energy and operational performance.

4.1 BAS Product Selection and Bidding

There are many products on the market that can achieve a high-performance BAS, and most, if not all, modern (current generation) DDC systems should be able to support the use of G36 sequences. However, there are additional considerations to obtaining a well-functioning, long-lived BAS installation at a reasonable cost. Most of these apply whether G36 is to be used or not.

> It is important to understand how BAS products differ from other commodity HVAC equipment such as fans, motors, and VAV boxes. Similar HVAC products from different manufacturers are often interchangeable, allowing easy substitution. Moreover, any mechanical contractor can generally install or maintain any given equipment, regardless of who manufactured it. **This is generally not the case with BAS products.**

A building automation platform is a system that combines hardware and software components, so capabilities and ease of use can vary widely from one manufacturer to the next. If one looks from the perspective of the installer or programmer, the difference between product lines is even greater. Practical considerations lead most installers to focus on one or at most a few different BAS platforms, so the initial choice of BAS product line may have long-term implications for the installer relationship and the availability of service.

These unique realities of the BAS market suggest several best practices for selecting a BAS platform:

- **Consider multiple manufacturers**: Although they all perform similar core functions, different manufacturer's platforms provide very different interfaces and secondary capabilities. Some interfaces offer impressive functionality to operators and commissioning providers, such as powerful trend viewing capabilities, audit logs, override and TAB reports, and global overrides. It is worthwhile for the designer to investigate multiple options and discuss needs and preferences with the building operators or owner's representatives.
- **Avoid installer lock-in:** Installer specialization means that, particularly in rural areas, there may only be one contractor who is able to work on a given platform. In urban areas, a similar lack of

competition is enforced by some manufacturers, who grant regional exclusivity to a single installer. If possible, these situations should be avoided because they create an uncompetitive bid situation not only at installation, but also for all maintenance and future expansion for the lifetime of the BAS. Consider selecting a BAS product or manufacturer with multiple local installers to avoid installer lock-in and enable competitive bidding.

- **Avoid lock-in for service contracts:** Some manufacturers have multiple contractors that can compete for new installation within a given geographic area, but they have agreements that prevent competition for service contracts. This forces the owner to use the same installer who won the initial bid for ongoing service or future work at the same site, which prevents competitive bidding and leaves the owner with few options if the contractor does not perform. Owners should consider the long term service options for a BAS when selecting a platform.
- **Provide tight, coherent, complete, and unambiguous BAS specifications and drawings:** Quality specifications are important for all disciplines, but the inherent complexities of BAS make it especially important for these products. Before issuing drawings for bid, the specifying engineer should carefully review the sequences, points lists, and control drawings from the Guideline. Make sure that it is clear which sequences apply to which equipment and that all the all the setpoints required from the designer are included. Finally, the engineer must provide a BAS hardware specification (which is not included in G36) and add language to their TAB specification to establish field-determined setpoints and coordinate those results with the BAS installer. Providing all of this information helps streamline the BAS delivery process, reduce change orders, and ensure an enforceable specification for a high-performance system.
- **Communicate and coordinate early and often:** Installing a BAS is a complex process that requires input and engagement from the design engineer, the mechanical contractor, the controls contractor, the TAB contractor, the commissioning provider, and the building operators. Coordination is important in any aspect of construction, but with BAS it is essential to a successful project and to ensure compatibility between mechanical and controls components. Take the time to communicate and get to know the other parties early in the process. RFIs are necessary for documentation, but do not rely on them as a primary means of communication. In addition to being impersonal, they are too slow to keep pace with the BAS installation process. Exchange emails or phone numbers, and plan to talk to each other throughout the project.
- **Require basic IT security:** The security of computer systems, particularly those that control physical infrastructure, has become a topic of general concern. While the topic of IT security is far beyond the scope of this document, it is important to take at least the most basic precautions. The BAS network (as well as the rest of the building's IT) must be behind a firewall. The BAS portion of the network should be segregated from the regular IT portion with a virtual (or separate physical) LAN. Control panels should be installed in physically secure locations unless provided with a lock. User login credentials should be specific to each user to enable audits of changes made to the system. If the system is remotely accessible, it should not be publicly accessible through the internet without use of a virtual private network. Additionally, passwords should be strong and updated frequently. There should be an update path for all software and firmware used in the BAS, the bid cost should include software updates for many years (not just the warranty period), and a process should be defined to ensure that security patches are applied. Many of these requirements can be specified by the designer, but ensuring they remain effective over time requires ongoing engagement from the building operators, supported by owner policies.

4.2 Setpoints

Providing initial/default values for all setpoints in the construction documents saves guesswork on the part of the installer and helps ensure a consistent result. To make this easier, G36 provides consolidated lists of the setpoints used in the control logic.

Part 3.1 of G36, "Information Provided by Designer" is a list of the project-specific setpoints and variables referenced in the terminal unit and AHU sequences. Informative Notes provide context and guidance with defaults for many of the values. The specifying engineer will ideally review all these defaults to verify that they are appropriate for their project. However, there are a few pieces of information that the designer **must** provide to enable a functional system.

Principally, the designer must decide whether ventilation is per Title 24 or ASHRAE Standard 62.1. They must also provide the outdoor air requirements for each zone, the primary cooling (and heating if applicable) airflow setpoints for each zone, and the outdoor air setpoints for each AHU. This information is most easily conveyed via the zone and AHU schedules on construction drawings.

The precise information required depends on the ventilation code being used. This is described by Informative Notes in the Guideline and summarized in Table 4.

Table 4. Design Ventilation and Airflow Requirements

	ASHRAE Standard 62.1-2018		Title 24-2019	
Zone ventilation requirement	People-based component	Vbz-P	People-based component	Vocc-min
	Area-based component	Vbz-A	Area-based component	Varea-min
Zone primary airflow setpoints	Minimum	Vmin[3]	Minimum	Vmin[3]
	Maximum	Vcool-max	Maximum	Vcool-max
	Heating maximum (reheat zones only)	Vheat-max	Heating maximum (reheat zones only)	Vheat-max
AHU outdoor air setpoint	Uncorrected design outdoor air rate	DesVou	Design outdoor air rate with demand controlled ventilation (DCV) zones empty	AbsMinOA
	Corrected for ventilation efficiency	DesVot	Design outdoor air rate with DCV zones populated	DesMinOA

[3] In the 2018 version of G36, Vmin must be specified by the designer for each zone. Starting with the 2021 version, Vmin may be calculated automatically based on the zone outdoor air requirements and other factors.

The designer should also provide zone group assignments for every zone, again typically as a schedule on drawings. Although some rules of thumb and a zone group table are included in Part 3 of the Guideline, the table provided is merely an illustrative example and not sufficient for project execution.

Part 3.2 of G36, “Information Provided by (or in Conjunction with) the Testing, Adjusting, and Balancing Contractor” also lists variables which are referenced in the sequence logic, but these values—fan speed limits, damper limits, and differential pressure setpoints—must be determined by testing after the mechanical system is constructed. To avoid a substantial change order, the specifying engineer should **include the necessary language in the TAB specification itself,** so that this work is bid into the TAB contractor’s scope.

> For each setpoint determined during TAB, the description includes the test condition required to determine it (e.g., *MinSpeed - The speed that provides supply airflow equal to DesOA with the economizer outdoor air damper fully open*) and Informative Notes provide examples of TAB language that can be used. During the actual test and balance phase of the project, the designer or commissioning provider should coordinate between the controls installer and the TAB contractor to ensure that values programmed in the BAS are updated based on the results of these tests.

4.3 Control Hardware and Sensors

Sensors, actuators, controllers, networking, and hardware requirements are outside of the scope of G36 and are addressed only peripherally in a few Informative Notes. As such, these topics must be covered by a separate Division 23/25 BAS hardware specification. For the most part these requirements are straightforward, but there are a few important hardware considerations to achieving a high-performance BAS.

4.3.1 BAS Controllers

As noted previously, most modern BAS product lines should be able to support high-performance control sequences. However, not every controller in every product line can do. Advanced sequences generally require that the controllers be fully programmable and to have enough capacity to handle the associated logic, whether in terms of memory or software limitations such as number of programming blocks or variables. *Configurable* controllers, where the installer selects one of several options from a library of pre-programmed control logic, are not suitable unless the controller’s pre-programmed library includes the G36 sequences.

This is not typically a concern for new building controller-level hardware, as they are most often fully programmable devices. However, some modern product lines include both fully-programmable and configurable/non-programmable options for application-specific controllers and VAV box controllers. Always specify the fully-programmable product (preferred, for flexibility and adaptability) or require configurable controllers to be provisioned with G36 logic. Some manufacturers offer fully-programmable controllers and a library of G36 sequences already implemented in their native language, ready to upload—this is the best of both worlds. However, there is currently no independent validation of the quality, completeness, or adherence of manufacturer programming libraries to G36. A CEC-funded effort developed a pilot approach to conduct bench-scale automated testing but additional work is needed to develop a standard or certification process. (Cheng, Singla, & Paliaga, 2022)

4.3.2 Network Architecture

Traditionally, DDC networks use Ethernet for backbone communications and master/slave token-passing (MS/TP) or other low-bandwidth protocols for communication to terminal units and field devices. More recently, some BAS manufacturers have begun to offer product lines consisting of IP-based controllers (meaning that all network communication is via TCP/IP over high-bandwidth Category 5 network cable).

Regardless of which network type is used, the designer should specify the project performance requirements for responsiveness (i.e., maximum time between command a response) and program execution frequency are met as the graphical interface, trending, commissioning, and zone-demand-feedback features of G36 do require more bandwidth than traditional sequences of operation.

The network architecture, which is typically left to the BAS installer, should be designed to minimize network traffic by locating zonal request logic within the zone controllers, where possible. It is also recommended that point aggregators are used to totalize requests, determine Zone Group modes, and to broadcast system data to zone controllers within the associated Zone Group to further reduce the network traffic on the backbone. The point aggregator programming should reside on building controllers or advanced application controllers, which reside on both the network backbone and zone controller subnets.

In some applications, such as retrofits where configurable zone controllers are used, it may be necessary to poll all required points from zone controllers and generate requests within a point aggregator. While point polling is less than ideal, network traffic can be reduced by increasing the point update intervals or by setting network points to update on change of value subscriptions.

4.3.3 Zone Feedback/DDC to the Zone

High performance sequences, including but not limited to G36, use demand-based resets to ensure that comfort conditions are maintained while minimizing energy consumption. Effective demand-based resets require feedback from every occupied zone in the building. This means, at the very least, real-time measurement of zone temperatures. Ideally, this includes the damper position, airflow, and the signal value of the zone temperature control loop as well (G36 requires all of this). Installing DDC only at the plant level and using pneumatic controls at the zone level severely limits the opportunities for energy efficiency. Conversely, zone feedback enhances the operator’s ability to understand how their building is functioning, see Figure 21 for an example. Budget for and specify DDC control at every occupied zone.

4.3.4 AHU Damper Actuators

It is common to control the outdoor air, return air, and exhaust air dampers of an AHU from a single point, and in many cases using a single actuator. In this configuration, the outdoor and return air dampers are complementary, and the exhaust air damper matches the outdoor air damper position. However, G36 controls multiple-zone VAV AHUs dampers independently. The outdoor and return air dampers are sequenced, rather than complementary, so one of the dampers is always fully open during economizer operation to minimize pressure drop and fan power. The purpose of the dampers is to vary the outdoor air fraction; resistance is minimized by modulating each damper one-at-a-time, rather than by potentially having both dampers partially closed at the same time. This means that a separate control point and actuator is required for each of the three dampers. To reduce costs, a single-zone AHU may use a common actuator and point to control the outdoor air and return air dampers.

4.3.5 Building Pressure Sensors

Controlling return or relief fans to a building pressure setpoint is a common strategy and is among the options for AHU control with G36. The intent of building pressure control is to maintain relatively neutral building pressure control as system operation and outdoor airflow rates vary. High positive pressurization may blow or hold exterior doors open, which may be a security issue or lead to whistling noises at doors and windows. Negative pressurization may lead to exterior doors becoming difficult to open or slamming shut, which may be safety issues. Maintaining a slight positive pressurization reduces infiltration to help control thermal loads, keep out outdoor air pollutants, and in humid climates to reduce moisture infiltration in the building envelope. Because the building pressure setpoint is typically quite low—a value of 0.05” is common—the building pressure sensor must be both precise and accurate for stable and effective control. For this reason, a fixed-range sensor with a narrow range (e.g., -0.25 to +0.25”) is strongly recommended. **Adjustable-range sensors, which are common and inexpensive, are acceptable for higher-pressure applications (such as duct static) but should be specifically disallowed for building pressure control due to inherent inaccuracy.**

Even in the best of circumstances, building pressure can fluctuate rapidly and is nonuniform throughout the building, so it can be difficult to measure an accurate and meaningful signal. For this reason, building pressure sensors should not be placed where they will be influenced by wind effects, stack effect, or unbalanced ventilation between zones, so entry lobbies, elevator lobbies, and zones with a lot of transfer air should be avoided. Though one of the main purposes is to avoid excessive pressures at the exterior doors, the pressure fluctuations when doors open and close can lead to excessive control instability. The high pressure port should be placed in large interior zones such as open office without operable windows or doors nearby. The low pressure port should be piped to a high point on the outside of the building through a high-volume accumulator or otherwise protected from wind fluctuations. In addition, it is a good idea to use a rolling average of building pressure for control (G36 uses a 5-minute average with 15-second sampling frequency) to dampen the inevitable fluctuations.

4.3.6 Coil Leaving Temperature Sensors

Accurate measurement of air temperatures is crucial to reliable and energy-efficient HVAC operation, particularly coil leaving or SATs. Nevertheless, measuring representative air temperatures leaving heating or cooling coils can be challenging. It is not simply an issue with sensor accuracy; asymmetry in temperature distribution and radiant heat transfer from coil surfaces may lead to non-representative temperature readings.

It is not uncommon to encounter temperature stratification across heating and cooling coils. Airside economizers are notorious for temperature stratification—the outdoor and return air streams often do not mix well, leading to temperature stratification that may persist even downstream of heating and cooling coils. Duct temperature sensors are typically single point sensors with probe lengths varying between 6 to 18 inches long. A point sensor that is located on one side of a supply duct may be exposed to temperatures from only one of those airstreams. For hydronic coils, during low water flow conditions much of the thermal energy may dissipate near the header side of the coils, which may lead to temperature stratification across the width or height of the coil, depending on the coil configuration. For large coils, consider installing two SAT sensors and controlling based on the average, particularly where coils are divided into multiple sections and may have more than one control valve. Use of an averaging sensor may also be a consideration but note that averaging sensors have a slower response time and require access and some sort of structure for support. Stratification is also suspected to be an issue for hot water reheat coils at low water flows—a project funded by the CEC is expected to research this effect in laboratory testing in 2022.

Another risk to accurate temperature readings is radiant heat transfer from coil surfaces to temperature probes that are located too close, mainly downstream of heating coils where there may be a large temperature differential. Temperature sensors should be located as far upstream or downstream of coils as possible, six inches minimum.

4.3.7 Outdoor Air and Economizer Temperature Sensors

OAT is often used to enable/disable equipment, and it may be used to reset supply air or water temperatures. OAT is also used to enable or disable the AHU’s air economizer. However, OAT is not necessarily uniform across a building site, and the measurement is subject to adverse influence from direct sunlight and weather conditions. Often OAT sensors at AHU intakes are located inside the dampers and do not provide valid readings when the fans are off.

Because of the importance of this point for HVAC system control, it may be worth installing multiple sensors. Ideally, a large project with multiple AHUs will have an OAT sensor at the outdoor air intake, as well as a global OAT sensor installed in a shielded, aspirated enclosure out of direct sunlight.

> The global sensor should be in a shielded enclosure, and the enclosure should be installed where it will remain out of direct sunlight throughout the day. By itself, the enclosure’s sunshield is not sufficient to prevent undue solar influence. For additional accuracy, an aspirated enclosure can be specified.

If there are multiple sensors, the OAT reading used for control should be the average of valid sensor readings between global sensors and sensors at AHU intakes. OAT sensors AHU intakes should be considered valid on when the supply fan is proven on, and the unit is in Occupied Mode or any other mode with the economizer enabled. If enough sensors are available, the lowest and highest readings—which are most likely outliers—can be discarded for better accuracy. A global sensor measurement should always be provided for use as the basis for optimum start when no AHUs are operating.

4.3.8 AHU MAT Sensors

The temperature in an AHU’s mixed air plenum is notoriously difficult to measure accurately. Turbulent air flows and the confluence of airstreams at very different temperatures create a high degree of thermal nonuniformity. For this reason, MAT should generally not be used for critical control functions like economizer or SAT control.

Nonetheless, there is value in knowing MAT with a reasonable degree of accuracy. G36 does not use the point for control, but it does use it for economizer fault detection and diagnostics. Because of the high prevalence of economizer faults, this is a function that should be supported by the control system design. In addition, an accurate MAT is very helpful to commissioning providers and operators who are trying to understand system dynamics or diagnose a problem.

An averaging sensor, installed across the full width and height of the plenum or filter bank, is the best way to obtain a reasonably accurate MAT reading.

4.3.9 VAV Box Discharge Air Temperature Sensors

Dual-max VAV control logic—which is a core energy-efficiency strategy as well as being mandated by Standard 90.1 and Title 24—requires a DAT sensor at each reheat terminal unit. Controlling the DAT to a resetting setpoint prevents overheating of the supply air, which can cause stratification, discomfort, and inefficient heating. There are no special requirements for the sensor itself—any standard properly installed single-point duct sensor is acceptable. However, these sensors are not required by most older control strategies, so it is important that they be shown on control drawings and in points lists and included in the bill of materials at bid.

4.3.10 CO_2 Sensors

DCV is a strategy that prevents over-ventilating spaces with high design occupant density (such as conference and classrooms) during periods of partial occupancy. Typically, the concentration of carbon dioxide (CO_2) is measured in the room as an indicator of occupancy, as CO_2 is a bioeffluent emitted by occupant respiration. When CO_2 concentrations are low, airflow can be reduced to area-based ventilation requirements. When CO_2 concentrations are high, the system increases airflow and outdoor air rates. **DCV is required by Standard 90.1 and Title 24.**

CO_2 sensors are generally optical devices that drift over time as their sensor beam ages and is fouled by airborne particulates, so some method of recalibration or error correction is required. They are also sensitive to shock. A hard impact can permanently ruin their accuracy, so they should not be dropped or otherwise abused. Laboratory tests by the Iowa Energy Center found a wide variation in CO2 transmitter performance where none of the tested models met the manufacturer-reported accuracy statements when new, let alone after accounting for sensor drift over time. (National Building Controls Information Program, 2009) Some sensors performed better than others, and more consistently, across the three that were tested for each product.

For most spaces, automatic background calibration (ABC) sensors are the best choice. These units recalibrate themselves by assuming that the lowest level measured over a period of time—which presumably occurs when the building is unoccupied—is equal to the ambient level of ~380 PPM. Many BAS manufacturers offer temperature sensors that have optional integrated CO2 sensors, which can significantly reduce installation cost.

ABC-type CO_2 sensors are not suitable for spaces that have continuous occupancy for obvious reasons. In those spaces, install dual-beam sensors that use a second reference beam to compensate for changes over time. However, these sensors are more expensive and cannot correct for other sources of drift.

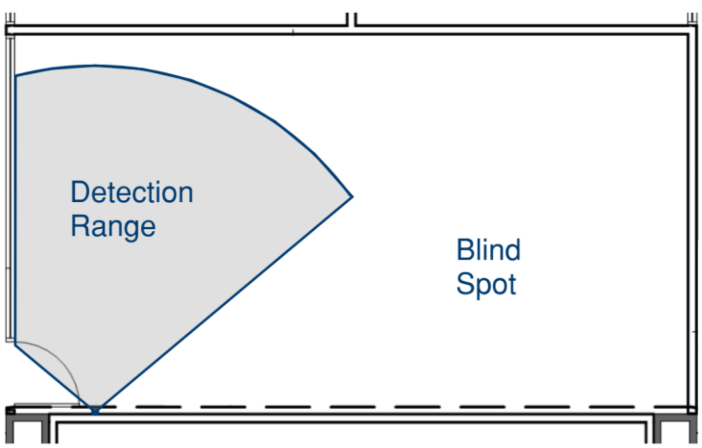
Age-related drift can be reduced and accuracy improved by using sensors that have a solid-state light source (similar to an LED) rather than a traditional incandescent source, though this increases cost.

Many BAS manufacturers offer room temperature sensors that optionally include integrated CO2 sensors. This significantly reduces installed cost as the incremental sensor cost is generally lower than for stand-alone devices, and there is no additional field installation or wiring required.

4.3.11 Occupancy Sensors

Occupancy sensing for HVAC control is a relatively new application but one that has grown rapidly in new construction due to new building energy code requirements (see Section 3.4.6). Nevertheless, accurately sensing occupancy can be challenging, and there are a number of implementation issues to consider.

There are generally two occupancy sensing technologies used in building applications: passive infrared (PIR) and ultrasonic. PIR or motion sensors generally detect body heat but need relatively large movements and unobstructed line-of-sight to detect occupant presence. PIR sensors are common and inexpensive but prone to false negatives. For example, a PIR sensor might not detect an occupant that is sitting still at a workstation, too far away, or at a sharp angle to sensor, and cannot detect occupants around a corner or if its field of view is blocked by furniture. Ultrasonic sensors, which work by bouncing ultrasonic waves off of objects and detecting a frequency shift between the emitted and reflected sound waves, are better at detecting minor motion and do not require direct line-of-sight. Dual technology sensors combine both PIR and ultrasonic technologies. Generally, both technologies must detect an occupant in the room to sense presence, but only one needs to continually sense the occupant to maintain presence.



A wall mounted PIR sensor integrated with the room temperature sensor and located by the door can only detect occupants over a portion of the room. Based on a typical sensor with 15-ft distance and 100-degree horizontal view.

Figure 18. Field of View for Typical PIR Sensors

Common approaches to using occupancy sensors:

- **Integration to networked lighting control (NLC) system.** Building energy codes have required occupancy control for lighting systems for many years. That market is mature in new commercial construction and relatively common with lighting control retrofits as well. Occupancy sensors for lighting controls can use PIR or dual technology sensors and generally benefit from being ceiling- or fixture-mounted, often as an array for larger spaces, with good unobstructed view factors to the space. They have to be able to accurately detect occupant presence—false negatives that cause the lights to shut off would be an immediately noticeable nuisance for occupants. The occupancy controls can either be local (each sensor is only wired to and controls a single or set of fixtures) or networked (each fixture and occupancy sensor is addressable and can be individually controlled or monitored by a central controller). A benefit of an NLC system is that the occupancy sensors already exist for lighting control and can potentially be further leveraged for no-to-low cost for HVAC control through a network connection, such as BACnet. In practice, there are often network integration and coordination challenges with connecting to NLCs. In particular, lighting control zones are often not the same as HVAC thermal zones, and there are generally many occupancy sensors that need to be mapped to each thermal zone by either the lighting or controls installer. The lack of NLC industry standardization, ambiguity in contractor responsibilities, and inconsistent and confusing point naming schemes make this mapping process a challenge. Many lighting designers also simply do not specify NLC systems, perhaps due to lack of awareness of the benefit for BAS integration. Physically wiring the BAS to auxiliary contacts on the lighting control occupancy sensors is a possibility, but can be costly and suffer from coordination and other challenges.

- **Occupancy sensors integrated with room temperature sensors.** Many BAS manufacturers offer room temperature sensors (colloquially referred to as thermostats) with optional integrated occupancy sensors. This is a simple and low cost way to add occupancy sensing for HVAC control, since there is no additional field installation or coordination among trades required. However, this approach suffers from many potential drawbacks. Integrated occupancy sensors are generally PIR and prone to false negatives due to occupants that are motionless. Room temperature sensors are generally located on a wall at 4 feet above the floor, which may provide optimal field of view. PIR sensors generally cannot detect occupants in other rooms within the zone, around corners or behind furniture, beyond 15 to 20 feet away, or at sharp angles (Figure 18). False negatives run the risk of causing occupant discomfort or other dissatisfaction that may lead to the occupancy-based control being disabled.
- **Dedicated occupancy sensors.** BAS designers may choose to require dedicated occupancy sensors for HVAC control. This approach provides the flexibility (and also responsibility) to select different sensor technologies, placement, and quantity, but the additional devices and field wiring required may significantly increase installation cost.

4.3.12 Measuring Minimum Outdoor Airflow

Measurement of incoming outdoor airflow is challenging, but doing so accurately is critical to energy efficiency and indoor air quality. Matching the selection of the airflow measurement station to the application is key to avoiding chronic over- or under-ventilation.

A key design consideration is the range of air velocities that will be seen at the point of measurement. Every kind of airflow measurement station has a minimum and maximum velocity for accurate measurement. The designer must ensure that the incoming air velocity remains within these limits as the total airflow varies from minimum outdoor air to full economizer. For variable flow systems with a high turndown, this may require an AHU with separate dampers for minimum outdoor air and economizer (an option which G36 supports). The engineer may also be able to specify a unit with improved low-flow capabilities (i.e., accurate readings at a lower FPM) at increased cost. In this case, careful review of submittals is essential, particularly for units that use a pressure transducer. The pressure transducer is an analog-to-digital device, and low-cost units can introduce substantial inaccuracy. The acceptable minimum and maximum velocity varies depending on product and technology, but respecting these limits is a consideration for all types of airflow measurement technology. A fixed range sensor with a narrow range is strongly recommended. Adjustable-range sensors, which are common and inexpensive, are acceptable for higher-pressure applications (such as duct static) but should be specifically disallowed for differential pressure across an outdoor air damper.

The quality of the air being measured is also a consideration. Airflow monitoring stations (AFMS), which use an array of sensing elements (typically either differential pressure or thermal dispersion), are affected by moisture and fouling. These systems should be installed downstream of filters (often not feasible for incoming outdoor air), or provision should be made for regular cleaning.

Finally, the designer must consider the AFMS location. Array-type AFMS require straight duct before and after the sensor array in order to be accurate. Rated accuracies are based on laboratory testing in ideal conditions, which are generally not found in real-world applications. Non-ideal placement can be mitigated to a degree by an airflow straightener, at the cost of increased static pressure drop. In a variable-flow system, the static pressure loss may be unacceptable at maximum airflow. Alternatively, some units can be field calibrated, but this is a painstaking process, and the results may not be accurate across a range of airflows due to turbulence. In real applications, non-uniform airflows, turbulence, and the effects of wind may also contribute to measurement error.

These last issues can be minimized with an AFMS that measures pressure drop across a louver with a known velocity/pressure profile. These devices are somewhat less accurate in theory than array-type AFMS but are much more robust against dust accumulation. They also do not require straight duct or an airflow straightener, making them easier to install at an AHU outdoor air intake. Unlike array-type AFMS, these devices do not create additional pressure drop, beyond that of the louver; however, their accuracy is a function of the louver's pressure drop (greater ΔP provides greater accuracy and measurement range), and the louver selection limits the maximum acceptable air velocity.

Additional guidance on selecting airflow measurement devices is available in the ASHRAE Journal's Selecting and Specifying Airflow Measurement. (Duda, 2019)

4.4 Graphics, Data Management, and User Interface

Another important element of a high-performance BAS is an operator's interface that is logically organized, well-presented, and easy to use. If the system is hard to understand or awkward to use, it will significantly limit the operators' ability to identify problems and diagnose malfunctions.

A strong BAS specification will provide a significant amount of guidance and detail on various elements of the operator's interface and the user experience. As with control hardware, these details are outside of the scope of G36, and they must be included in the construction documents as part of a separate Division 23/25 specification.

Every control product manufacturer has their own approach and solution for front end (user's interface) and back end (database) software, but any of them should be able to support these suggestions. Ensuring that the installer follows these best practices will reduce the burden on the operators and make it easier to maintain good system performance over the long term.

4.4.1 Interface Graphics Best Practices

Following these best practices will enhance the usability of any building control system.

- **Include a Floorplan:** For any but the simplest systems, the home page should be a graphical depiction of the building layout, with equipment located approximately as it is in real life. From this page, the operator can click through to examine any zone or equipment in detail. Floorplans of spaces should graphically display temperature control by coloring the zone area relative to setpoints to allow operators to quickly assess system operation. Room numbers and thermostat locations should be included on the floorplan graphics to aid in locating equipment and devices.
- **Provide summary table graphics for similar equipment:** Most commonly for VAV boxes, a single text-based page (or as few as possible) should be provided showing operating mode; airflow rate; airflow rate setpoint; zone temperature; active heating setpoint; active cooling setpoint; damper position; HW valve position (reheat boxes); SAT (reheat boxes); SAT setpoint (reheat boxes); CO_2 concentration and CO_2 loop output (where applicable); Fan start/stop command, speed, and status (fan-powered); static pressure reset current requests, cumulative %-request-hours, and request Importance Multiplier; Cooling SAT Reset current requests, cumulative %-request-hours, and request Importance Multiplier; Heating HWST Reset current requests, cumulative %-request-hours, and request Importance Multiplier (HW reheat). Similar tables should be provided if there are multiple AHUs, fan coils, heat pumps, etc. to allow for rapid inspection of similar equipment.
- **Use Color Intuitively:** Indicator lamps and text readouts should use color in a logical fashion (e.g., green for operating; red for a fault condition; grey if the equipment is off). Each of these indicator lamps should also be labelled with text to accommodate the color blind population.
- **Label Everything, Unambiguously:** Every major device shown on the overview should have an equipment tag showing, and each device-specific page should clearly identify the equipment to which it applies. Review the graphics to make sure that all displayed text is unambiguously associated with a device. Avoid situations where, for example, a temperature value is displayed equidistant between two temperature sensor icons such that it is unclear to which sensor the value belongs. This very common user interface shortcoming introduces a lot of unnecessary uncertainty, making life more difficult for the operators.
- **Show All Key Points, Setpoints, and Parameters.** All relevant inputs and outputs, setpoints, and key parameters being controlled or monitored should be displayed on a graphic with the appropriate engineering units (e.g., degrees or inches of pressure, not 0-10VDC). Points should be adjustable or overridable from the graphics without requiring the user to navigate to the programming. Controlled variables should be displayed adjacent to the setpoints for clarity.
- **Support Timed Overrides:** The system should be programmed such that, by default, any point that is put in hand (overridden) will automatically revert to its pre-override state after a period of time. The reversion period should be something the operator can adjust, if necessary, because sometimes long-term overrides are required (e.g., for maintenance). But the default should be that the override is automatically released in no more than one day.
- **Clearly Flag Overridden/In-Hand Points:** If the user interface makes it visually obvious when a point is overridden, it reduces the chance that it will be left that way by accident. The system should also be able to generate a report that lists all overridden points. Ideally, this report is automatically generated on a regular basis to prompt the operators to review the system and

release any extraneous overrides. While this requirement may seem redundant with the previous one, it is not. Accidental long-term overrides are a major problem, so a two-tiered approach to preventing them is a worthwhile investment.

- **Require Hyperlinks to Associated Equipment:** Terminal graphics should have links to associated air handling and hot water plant equipment and air handling unit graphics should have links to associated chilled and hot water plant equipment, as applicable, for ease of navigation.
- **Require Screen Penetration and a Back Button:** After drilling down to the level of a specific device, the operator should have the ability to navigate back one level at a time or to other graphics logically without going all the way back to the main/home screen. This simple feature can greatly streamline operator workflow.
- **Require Separate Logins for Users:** Computer security, particularly the security of control systems, is a subject of great and growing concern. If each user has their own login credentials, it is much easier to enforce access control, audit user behavior, and detect if a user account has potentially been compromised.
- **Do Password Due Diligence:** Weak passwords and unchanged default passwords are among of the most common vulnerabilities in IT systems. **Explicitly require that all default passwords be changed during installation.** Also establish a policy using strong passwords or a pass-phrase. A nonsense pass-phrase (e.g., "CrossBucketFierce" from https://randompassphrasegenerator.com/) can be easier to remember than a random string of letters and numbers and is secure by virtue of its length.
- **Make the Systems Manual Accessible:** The commissioning provider should provide a systems manual or the contractor an operations and maintenance manual that includes, among other things, approved submittals, construction documents, and operations and maintenance materials for both the mechanical system and control system (and other systems, like lighting, when applicable). This document should be provided and reviewed before final handover. Store this document as a PDF where the operator can easily access it and ensure that they know how to find it. Storing an electronic copy of the files on the server with hyperlinks from the graphical interface makes these files readily accessible to operators. Also back the document up to a flash drive, in case the server is accidentally wiped.

4.4.2 Select Interface Examples

The following example graphics are meant to be illustrative; actual graphics will depend on the BAS platform and installer.

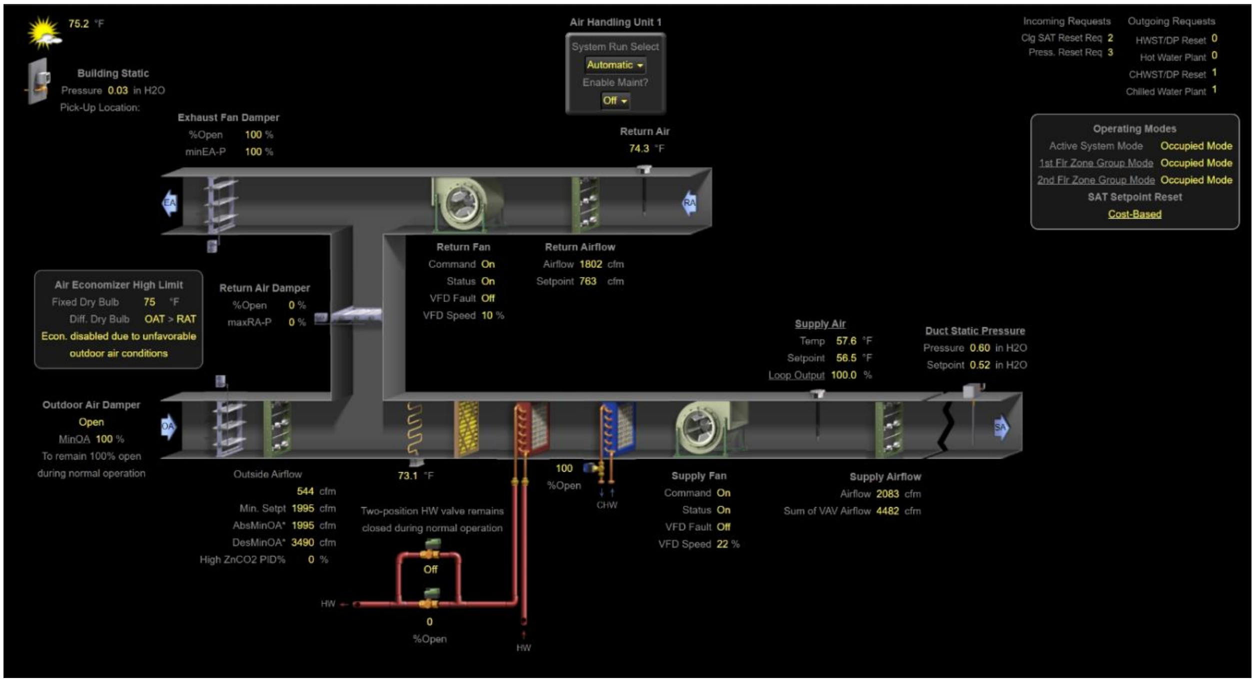


Figure 19. Example Air Handler Graphic

Figure 19 above is an example of a well-designed, well-organized, and clearly-presented summary screen for a VAV AHU with return fan. The mode the AHU and of each zone group it serves is clearly displayed, and the status of fans and position of dampers are intuitively represented by animations. All key points, both hardware and software, are displayed on the graphic and clearly associated to the relevant sensor or device. Both the setpoint and measured value are shown for every controlled parameter, so the operator can clearly see when control is lost or unstable. T&R requests are summarized, including both incoming requests (from zones, to reset SAT or DSP setpoints) and outgoing requests (to CHW and HHW plants). Though it is not obvious from the image, hyperlinks allow the user to drill down for more information, such as details about the T&R loops or additional data from the VFD.

During point-to-point testing, it is important to verify that the damper and valve position feedback shown on the graphic match the actual commanded positions.

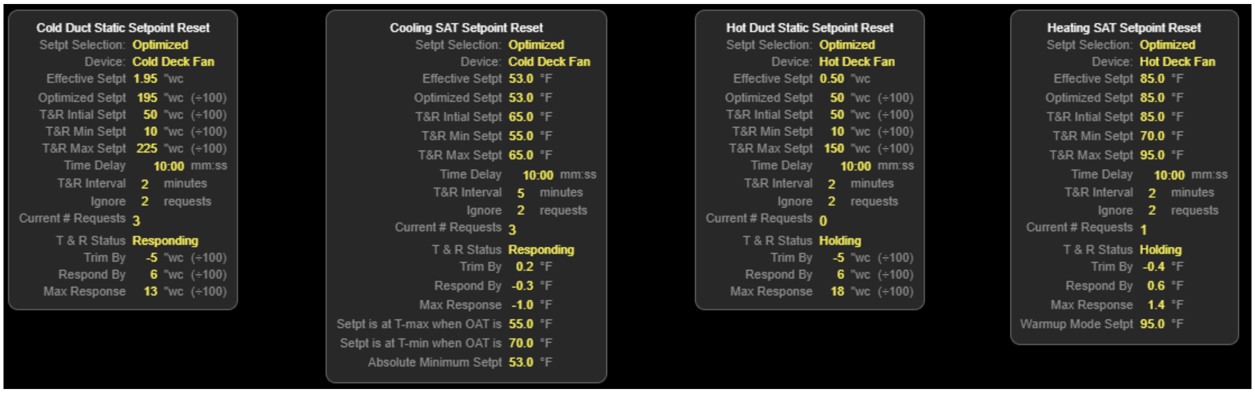


Figure 20. Example Trim & Respond Summary Graphic

Figure 20 above displays all of the parameters for several distinct T&R reset loops. A page like this should be accessible as a hyperlink from the AHU graphic like the one shown in Figure 19. Note that this example is for a dual-fan, dual-duct AHU, so there are four separate T&R loops represented: one for static pressure setpoint reset and one for SAT setpoint reset for each of the cold deck and the hot deck. All of the factors shown (except for “Current # Requests” and “T&R Status”) are adjustable by the user for tuning.

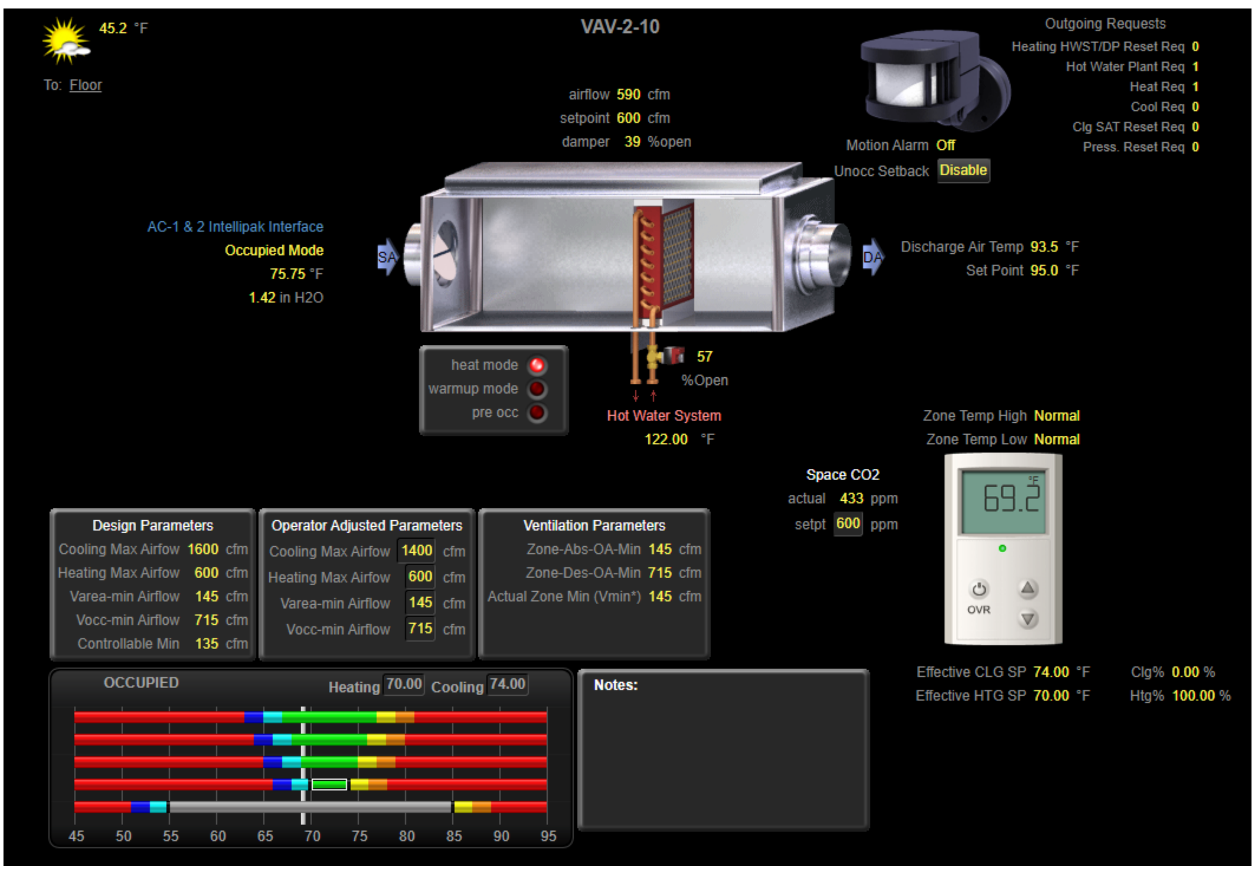
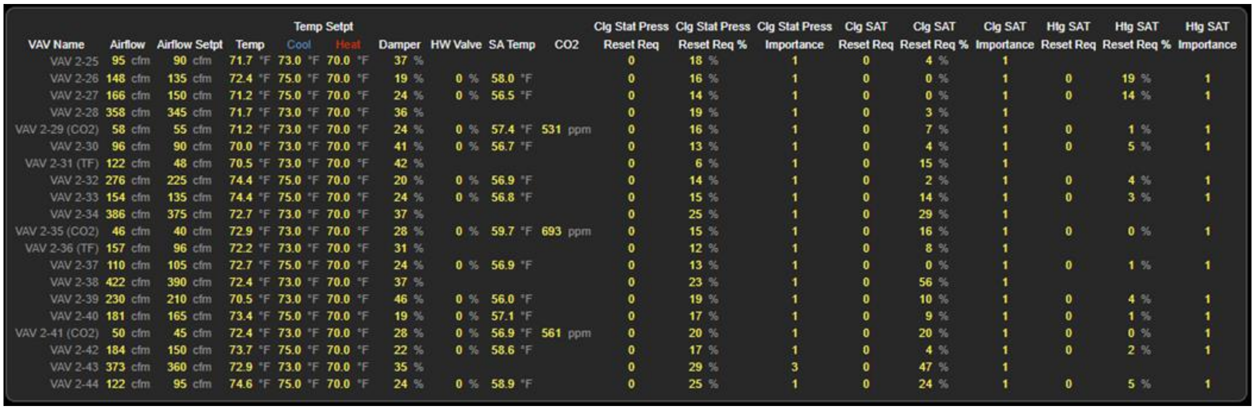


Figure 21. Example VAV Reheat Zone Graphic

Figure 21 above is an example of a user interface screen for a single zone and its VAV box. It has many of the same design features as the AHU graphic, with unambiguous labels showing both setpoint and actual measured values. In addition, the screen shows both current ("operator adjusted") and original ("design") airflow limits and ventilation requirements. The design parameters have no control effect (and should NOT be adjustable by the operator), but retaining them allows the operator to easily see if they have been changed from the original and restore them if necessary. All T&R requests—outgoing, to the AHU—are shown along with the importance multiplier for each type. This graphic contains hyperlinks to other interface graphics—in this case, to the AC unit, hot water system, and to the floorplan graphics.



VAV Name	Airflow	Airflow Setpt	Temp	Temp Setpt Cool	Temp Setpt Heat	Damper	HW Valve	SA Temp	CO2	Clg Stat Press Reset Req	Clg Stat Press Reset Req %	Clg Stat Press Importance	Clg SAT Reset Req	Clg SAT Reset Req %	Clg SAT Importance	Htg SAT Reset Req	Htg SAT Reset Req %	Htg SAT Importance
VAV 2-25	95 cfm	90 cfm	71.7 °F	73.0 °F	70.0 °F	37 %				0	18 %	1	0	4 %	1			
VAV 2-26	148 cfm	135 cfm	72.4 °F	75.0 °F	70.0 °F	19 %	0 %	58.0 °F		0	16 %	1	0	0 %	1	0	19 %	1
VAV 2-27	166 cfm	150 cfm	71.2 °F	75.0 °F	70.0 °F	24 %	0 %	56.5 °F		0	14 %	1	0	0 %	1	0	14 %	1
VAV 2-28	358 cfm	345 cfm	71.7 °F	73.0 °F	70.0 °F	36 %				0	19 %	1	0	3 %	1			
VAV 2-29 (CO2)	58 cfm	55 cfm	71.2 °F	73.0 °F	70.0 °F	24 %	0 %	57.4 °F	531 ppm	0	16 %	1	0	7 %	1	0	1 %	1
VAV 2-30	96 cfm	90 cfm	70.0 °F	73.0 °F	70.0 °F	41 %	0 %	56.7 °F		0	13 %	1	0	4 %	1	0	5 %	1
VAV 2-31 (TF)	122 cfm	48 cfm	70.5 °F	73.0 °F	70.0 °F	42 %				0	6 %	1	0	15 %	1			
VAV 2-32	276 cfm	225 cfm	74.4 °F	75.0 °F	70.0 °F	20 %	0 %	56.9 °F		0	14 %	1	0	2 %	1	0	4 %	1
VAV 2-33	154 cfm	135 cfm	74.4 °F	75.0 °F	70.0 °F	24 %	0 %	56.8 °F		0	15 %	1	0	14 %	1	0	3 %	1
VAV 2-34	386 cfm	375 cfm	72.7 °F	73.0 °F	70.0 °F	37 %				0	25 %	1	0	29 %	1			
VAV 2-35 (CO2)	46 cfm	40 cfm	72.9 °F	73.0 °F	70.0 °F	28 %	0 %	59.7 °F	693 ppm	0	15 %	1	0	16 %	1	0	0 %	1
VAV 2-36 (TF)	157 cfm	96 cfm	72.2 °F	73.0 °F	70.0 °F	31 %				0	12 %	1	0	8 %	1			
VAV 2-37	110 cfm	105 cfm	72.7 °F	75.0 °F	70.0 °F	24 %	0 %	56.9 °F		0	13 %	1	0	0 %	1	0	1 %	1
VAV 2-38	422 cfm	390 cfm	72.4 °F	73.0 °F	70.0 °F	37 %				0	23 %	1	0	56 %	1			
VAV 2-39	230 cfm	210 cfm	70.5 °F	73.0 °F	70.0 °F	46 %	0 %	56.0 °F		0	19 %	1	0	10 %	1	0	4 %	1
VAV 2-40	181 cfm	165 cfm	73.4 °F	75.0 °F	70.0 °F	19 %	0 %	57.1 °F		0	17 %	1	0	9 %	1	0	1 %	1
VAV 2-41 (CO2)	50 cfm	45 cfm	72.4 °F	73.0 °F	70.0 °F	28 %	0 %	56.9 °F	561 ppm	0	20 %	1	0	20 %	1	0	0 %	1
VAV 2-42	184 cfm	150 cfm	73.7 °F	75.0 °F	70.0 °F	22 %	0 %	58.6 °F		0	17 %	1	0	4 %	1	0	2 %	1
VAV 2-43	373 cfm	360 cfm	72.9 °F	73.0 °F	70.0 °F	35 %				0	29 %	3	0	47 %	1			
VAV 2-44	122 cfm	95 cfm	74.6 °F	75.0 °F	70.0 °F	24 %	0 %	58.9 °F		0	25 %	1	0	24 %	1	0	5 %	1

Figure 22. Example Zone Summary Graphic

Figure 22 above shows a zone summary graphic page, which allows the operator to review the conditions in multiple zones at once (single-duct VAV-reheat zones in this example). Airflow, SAT and zone temperature are all reported relative to their respective setpoints for each zone. In addition, this page summarizes T&R requests for static pressure, cooling and heating. For each zone, it displays both current requests and the percentage of time that the request is active ("Reset Req %"). Values of "Reset Req %" that greatly exceed those for other peer equipment may indicate rogue zone behavior (see Section 4.5.5 for details). In this case, VAVs 2-38 and 2-43 are potential rogue zones for the SAT reset.

4.4.3 Trends and Data Archives

Trends provide the operator with historical data about how the system has been operating under a variety of conditions. As such, they are an invaluable tool for understanding system behavior, troubleshooting, and identifying energy efficiency opportunities. Ultimately, they represent the data foundation of any smart building, as trends are the building's memory.

Historically, BAS trending capabilities have been constrained by hardware and network limitations, so that trends were only set up for a few high-level monitoring points or ad-hoc to help troubleshoot specific subsystems. A modern BAS platform, on the other hand, is much more capable. Unfortunately, many practitioners remain unaware of the great utility provided by a data-rich environment and continue to think of trends as an afterthought rather than a key tool for building management, so it is important both to include trend requirements in the Division 23/25 controls specification and follow up during commissioning to ensure that those requirements have been implemented.

- **Trend Comprehensively**: A modern BAS should trend *every* hardware input and output point, and as well as a large number of software points (variables). It is not necessary to trend every variable, but trending should include all software points that are used directly for control. In particular, this should include every controlled variable (both setpoint and measured value) and the total requests for each T&R reset loop.

- **Specify Trend Frequency:** High frequency trends can be very useful during testing and commissioning, so a sampling frequency of 5 minutes or less can be useful during this period. For actuator command points, consider using 1 minute or even 30 second frequency, to assist in loop tuning and to identify valves and damper that are hunting or chattering. The trend frequency may be reduced after post-installation testing and commissioning is complete to avoid overwhelming the database. For most points during normal operation, a sample frequency of 15 minutes is sufficient for ongoing monitoring.

> If one intends to reduce the sampling frequency after testing is complete, be sure to include this requirement in the specification, and verify that the change was made. Otherwise, the long-term collection of higher-frequency data may overwhelm the storage capacity of the trend database.

- **Require a Consistent Point Naming Scheme:** This is one of the most important and most often overlooked practices around data management in BAS. Point names are not specific to trending, as they are usually established during programming, but they greatly impact the practical value of the trend data and the ease of integration with third party analytics. Specify a hierarchical naming convention (e.g., Building.Floor.Room.Device.Point), enforce consistent capitalization and punctuation and require verification by the commissioning provider. Consider requiring the use of the Brick Schema (https://brickschema.org/). Brick is an emerging standard for building metadata, including the identification of sensors and control devices, and using it will help future-proof the control system. If naming is done consistently, it should be easy to find any given point in a list of names sorted alphabetically. If it is done inconsistently, it is hard to audit the system to ensure that all points are actually being trended, and the trend data becomes much harder to use effectively.
- **Apply Units:** Unless specified otherwise, the units associated with a trended point will often be left undefined or set to the default, which is usually wrong. Enforcing this simple detail can make the trend data much easier to understand and analyze.
- **Avoid Duplicate Trends:** In essentially all cases, any given point should only be trended once. Duplicate trends of the same point waste bandwidth and can create confusion.
- **Store Trend Data Long-Term**: Most BAS controllers can record a limited amount of trend data, after which the data must be uploaded to a database, or it will be overwritten in the controller and lost. Long-term data storage is often an additional cost, but it is a cost worth bearing for any complex BAS. One year's worth of storage enables the system's performance to be analyzed for seasonal impacts, while multiple years' make it easy to see how performance is changing over time. Both are very helpful in maintaining high performance over the life of the building. Historically, long-term trend data was stored locally on the operator's workstation or a dedicated database server. More recently, cloud storage options have become available; these services usually have an ongoing annual subscription cost but relieve the operators from having to maintain the database themselves.
- **Require Easy Export of Bulk Trends**: In many cases, it is desirable to export the trend data to a spreadsheet for further analysis. This process can be very simple, but it is often very complicated

and laborious due to limitations of the BAS software. For ease of use, the system should allow the user to select multiple trends and export them in bulk as a single file with a unified time stamp or as multiple files with one point per file. Trend solutions that only support exporting trends one at a time or fail to synchronize timestamps (i.e., each point has its own timestamp, and they do not all align) make sophisticated trend analysis more difficult. The Universal Translator is a free software tool that was specifically designed to streamline trend analysis where data streams have varying timestamps (http://utonline.org/cms/). Many systems do not allow for simple export of multiple trends, let alone bulk quantities of trends, which can make commissioning, analysis, and troubleshooting much more difficult.

4.5 Testing and Commissioning

For all but the most basic BAS, a full commissioning process is a critical final step to delivering a high-performance control system and an energy-efficient building. BASs are hard to do well—the hardware installation is very high-touch and usually done under unreasonable time pressure, while the programming is hampered by interface standards that lag decades behind the modern smartphone—so some mistakes are inevitable. Commissioning is a structured, systematic process to efficiently identify and correct these errors before the start of the warranty period. The organized and systematic nature of the process is key to its efficiency. Effective commissioning is more than simply a process, it should be results driven and focused on identifying and resolving issues. An effective commissioning provider (CxP) should be sufficiently knowledgeable and experienced to identify key issues and suggest remedies, and assertive enough to identify responsible parties and drive the team to a timely resolution. Owner's representatives may need to help provide motivation and enforcement. The need for attention to detail cannot be emphasized strongly enough; it is critical throughout the design and installation process, but particularly so in commissioning to ensure that the final result performs to the design intent.

4.5.1 Coordination

The need for coordination among project team members has been discussed elsewhere in this document, but its importance really cannot be overstated. The BAS is a complex system that involves multiple people, all from different disciplines and usually from different companies. Success requires that the project team members develop a common understanding of the design intent of the system. Doing so is a shared responsibility, but the team should identify one member—typically the CxP or the general contractor's commissioning coordinator—to take lead on BAS coordination.

Do not rely entirely on RFIs to communicate – they are too slow. Be prepared to talk amongst yourselves.

Ideally, the commissioning process begins no later than the start of the construction documents (CD) phase, with a design review of the mechanical system. If G36 sequences will be used, ensure that necessary sensors are included in the design. If other, custom sequences are to be used, the engineer should provide them to the CxP for review as early as possible and well before 100% CD.

At the start of construction, the BAS coordinator should organize kickoff a meeting with all BAS stakeholders including representatives from, at least, the BAS, mechanical and TAB contractors, the commissioning provider, the mechanical design engineer, and the general contractor's construction coordinator. The purpose is to get everyone up to speed about the design intent of the HVAC system and control strategy, discuss potential issues, and exchange contact information. As construction proceeds and the BAS installation begins, stakeholders should be prepared to communicate directly to resolve questions as they arrive. The RFI process should be used to document decisions and conclusions that arise from these communications, but the formal RFI process is too slow to support the generally hectic process of BAS installation. Develop direct channels of communication among project team members.

The kickoff meeting is also a good time to start discussing the sequences themselves. While final sequences may not yet be available, the specifying engineer should share their intent and operating strategy with the team, particularly any elements that are unusual or unique to the project. If G36 or other standardized sequences are to be used, this meeting is a good time to ascertain each team member's familiarity and comfort level and share this document or other educational resources listed in Section 7.

4.5.2 Pre-functional and Point-to-Point Tests

The purpose of pre-functional testing is to verify that the mechanical equipment and the control hardware are correctly installed and ready for functional testing. This work is the responsibility of the controls contractor, who should coordinate with the mechanical contractor and submit completed test forms to the commissioning provider for review.

Pre-functional tests should include at least the following activities:

- Complete the manufacturer-recommended startup process for all mechanical equipment to verify that installation is correct, power is available, fans spin in the correct direction, etc.
- Test hardware interlocks and hard-wired, life-safety connections.
- Verify that all BAS controllers have power and are communicating over the network.
- Perform network isolation tests to verify that controllers switch to stand-alone operation when network communication is lost and correctly recovery communications when the network is restored.
- Point-to-point tests to identify any sensor or actuator that is wired backwards or connected to the wrong controller.

The final step—point-to-point tests—are critical and should be performed for every hardware input and output point. The purpose of the test is to catch occasional, one-off wiring errors, so it is not sufficient to test only a sample of points. This process can be tedious, but it is worth taking the time to test thoroughly; any wiring errors which remain uncorrected at this stage will make subsequent functional testing—which is inherently more complex than pre-functional work—much harder and more time consuming. For this reason, **point-to-point tests must be completed and all deficiencies corrected before starting functional tests.**

Point to point tests should be performed for every hardware point – testing a sample is not sufficient.

While the controls contractor is performing pre-functional tests, the TAB contractor will be executing their scope of work. For G36 projects, that scope should include determining the setpoints listed under “Information Provided by (or in Conjunction with) the Testing, Adjusting, and Balancing Contractor” (see Section 4.2). The BAS coordinator should verify that these tests are performed and that the results are conveyed to the controls contractor after being reviewed by the design engineer. These parameters should be updated in the BAS before starting functional tests.

4.5.3 Functional Tests and Demonstration Tests

The purpose of functional testing is to check that the control logic behaves as expected and to verify that various pieces of equipment interoperate correctly. A rigorous functional test should exercise the system and programming through the full range of potential conditions through carefully scripted tests to compare performance against the expected response. A functional test can be as simple as checking that a variable speed fan can be controlled to meet a static pressure setpoint, or it can be as complex as verifying that a zone’s demand for cooling is correctly propagated upwards to reset the CHW supply setpoint at the plant. But in each case**, the purpose of the functional test is to verify control logic, not control system hardware/installation**. Hardware and installation verification should be completed during pre-functional testing, and the team should have confidence in the physical installation of devices before functional testing begins.

Point-to-point tests must be completed and all deficiencies corrected before starting functional tests.

The level of effort required for functional testing depends on the sequences being used. For simple sequences and simple mechanical designs, simple tests are usually sufficient. Complex sequences, including G36, require much more in-depth testing. However, if the control logic being installed was pre-programmed and pre-tested by the manufacturer, then functional testing can be less extensive and focus on aspects that are unique to the project. Some manufacturers are starting to offer pre-implemented G36 sequences for their installers to use.

T&R logic deserves special attention during functional tests, particularly if the control logic was written from scratch rather than drawn from a pre-tested library. A T&R reset loop traverses a range of setpoints; if incorrectly implemented, it may become stuck at one end or the other of the setpoint range. To avoid this, test the loop across its full range:

1. Start the loop with zero requests, and let it trim the setpoint to the minimum value.
2. Generate zone requests (using overrides). When the number of zone requests exceeds the number of Ignores, verify that setpoint starts to increase by the expected amount at each time increment.
3. Allow the loop to continue resetting the setpoint until it reaches the maximum value. Verify that this took the expected number of time increments to occur.
4. Remove the requests and verify that the setpoint resets back down.
5. Allow the setpoint to reset back to the minimum value.

> Note that this example is written for a T&R loop that controls a heating setpoint, because the setpoint trims downward and responds by increasing. A T&R loop that resets a cooling setpoint will show the opposite behavior, trimming the setpoint upwards and responding by reducing the setpoint. The T&R loop always trims in the direction of reducing energy intensity to meet a lower load and responds by increasing energy intensity to meet a higher load.

Functional tests should be performed by the controls contractor and test results reviewed and approved by the mechanical engineer before proceeding to demonstration tests. Multiple repetitions may be required if deficiencies are identified, but ultimately each test should be passed **in its entirety** before results are submitted for review. Trends for all hardware and relevant software points should be set up before functional testing, so system performance can be evaluated that way as well.

Demonstration tests, which repeat some or all of the functional tests in the presence of a witness, are independent confirmation that the functional tests were completed successfully. The purpose of separating functional tests from demonstration tests is to help ensure that the contractor is actually ready and has done his or her own review of the system performance. The key with demonstration tests is **the expectation that all of the tests will pass on the first attempt**. This expectation, which should be established in the BAS specification, requires the contractor to work through any issues that arise during functional testing, so that the demonstration can be performed quickly and efficiently. **If it is necessary to repeatedly interrupt the demonstration tests to fix issues as they arise, then the system is not ready.** As with functional tests, trends should be fully set up and enabled.

4.5.4 Trend Reviews

A trend analysis is often the last major step in a commissioning process, initiated after demonstration tests are successfully completed. Whereas functional tests are conducted under artificially overridden conditions, trend reviews evaluate systems under automatic control to verify overall system performance, control loop tuning, and the effectiveness of the setpoint resets. Often, trend reviews can identify programming issues, which were not discovered during functional testing or calibration, or point mapping issues that were not discovered during pre-functional tests. Project specifications should require trends to be enabled and set up for long term archiving and clearly indicate which points are to be trended. All hardwired points should be trended, in addition to key software points like setpoints, requests, and control loop outputs; if not specified, many necessary points are likely to be overlooked, limiting the effectiveness of the trend review process. The design engineer and/or the commissioning provider should review the trends and verify that system behavior is as expected. This means verifying the following at a minimum:

- Zone temperatures remain within deadband, during occupied and unoccupied periods when under normal control.
- Supply air and water temperatures consistently meet and hold setpoint, and setpoints are effectively reset for the season and conditions observed.
- Fans and pumps consistently meet and hold setpoint, and setpoints are effectively reset for the season and conditions observed (where applicable).
- Control loops are correctly tuned. Use high-frequency trends to identify hunting loops, dithering actuators, and chattering valves.

- All rogue zones have been identified and either corrected or locked out of the T&R reset loop.
- All BAS punchlist items have been corrected.

Some control system interfaces have powerful and effective trend viewing modules that allow for graphs to be saved, replicated automatically across similar equipment, and plot control points across several panes to evaluate complex control strategies. Other interfaces are much more limited in this capacity and not as effective for use in trend analysis. In these cases, exporting trends for offline analysis may be more effective, but a provision for trend export should be considered upfront. Many systems are not readily capable of exporting trends in quantity or only with the use of optional features with a cost add. The Universal Translator is a free software tool that was specifically designed to streamline trend analysis where data streams have varying timestamps (http://utonline.org/cms/). Third-party analytics that integrate to BASs are another option for facilitating trend analysis. These are often cloud-based, subscription-based services that provide feature-rich trend viewing capabilities as well as fault detection and diagnostic.

The use of trend reviews should not be limited to the commissioning of new projects. Trends can be a powerful tool to help troubleshoot system performance in existing buildings, particularly when a new issue has arisen. For this to work, trends must have already been set up and archiving. Setting up trends after an issue has passed is usually too late to be effective.

4.5.5 Rogue Zone Identification

Rogue zones are individual zones that too-frequently generate requests to a T&R loop. Rogue zones can occur due to programming error, design error (e.g., undersized VAV box), or conditions in the zone (e.g., someone put a coffee pot in front of the thermostat, generating false cooling demand).

It is critical to identify and remediate rogue zones. Otherwise, they can drive a T&R loop to its maximum setpoint, completely eliminating any energy savings from the reset across the entire system. At any point in time, different zones may generate requests, which is normal. A rogue zone is one that generates requests continuously or much more frequently than other zones. The easiest way to identify a rogue zone is to compare the cumulative “Request %” across similar zones. This is made trivial by simple inspection of an effective summary graphic (see Figure 22 for an illustration) but is otherwise very difficult to do effectively. Be sure to review the “Request %” value for each type of Request—static pressure, heating, and cooling—as a zone may exhibit rogue behavior relative to one parameter but not others. Any request % value that greatly exceeds those for other similar equipment should be investigated.

A rogue zone will “peg” a reset. Addressing them is critical to energy efficiency.

When a rogue zone is identified, try to determine what causes the zone to generate requests. Common causes:

- Zone is undersized for current cooling load, whether due to design error or a change in space use

- Zone is the critical run in the duct distribution and does not receive enough pressure to satisfy airflow setpoint
- Thermostat reads falsely high temperatures, affected by the sun, conduction through a perimeter wall, or appliances
- Zone airflow setpoint was adjusted higher than the design can handle
- Zone cooling setpoint was adjusted lower than the design can handle
- Zone heating setpoint was adjusted higher than the design can handle
- Zone serves a constant load, such as a server room
- Zone is affected by excessive infiltration in cold weather, such as exterior lobbies, that exceeds heating capacity

For rogue zones that cannot be easily remedied, consider locking them out of the T&R loop or increasing the number of ignores, so the reset can correctly respond to variable demand in other zones. Locking out a zone is most easily done by setting the rogue zone's Importance factor to zero. Either approach involves a tradeoff between maintaining airflow and temperature control vs. minimizing HVAC energy use. Where there are practical limitations to resolving mechanical design issues, consider the use of personal comfort stations. Desk fans are inexpensive, and low energy and can improve occupant comfort in warm conditions by locally increasing air movement. Chair heaters and electric space heaters may also be appropriate in cold conditions if they allow the overall HVAC system to operate more efficiently.

This process of screening for rogue zones is critical to good performance, because most of the energy efficiency benefits will be lost if the rogue zone is allowed to drive the reset.

4.5.6 Remedial Work and Handover

Once demonstration tests and trend review are complete, there will be a punchlist of remaining items to be resolved. It is important that these issues be addressed before the start of warranty, otherwise they will most likely never be corrected. After the contractor has completed the punchlist, repeat any associated tests to verify that the remediation is correct.

Do not start the warranty period until the BAS punchlist has been resolved.

Because the BAS is the last major building component to be installed, the final process of testing, correcting, and verification may extend past the start of occupancy. For this reason, the design engineer should specify that the BAS warranty period is independent of the warranty for other building systems. The BAS warranty should not be triggered by *substantial completion*, *beneficial use*, or the certificate of occupancy, but should only start when the specified acceptance criteria, including passing all functional tests and trend reviews, have been achieved.

5

Control
Retrofit Applications

- Screening
- Energy Savings Opportunity
- Cost Effectiveness
- Challenges with G36 Retrofits

5 Control Retrofit Applications

Though the best practices for new construction also apply to retrofit applications, there are additional issues to consider for retrofits, particularly around screening for feasibility and cost effectiveness. This section addresses retrofits that are primarily focused on control systems alone and those utilizing G36 sequences, but it excludes larger building renovations where architectural/mechanical elements are substantially replaced.

Control retrofits are generally initiated for a few different reasons:

- **End-of-service Life**: Existing control equipment is beyond its expected service life, no longer supported by manufacturer, spare part no longer accessible, pneumatic controls
- **Energy Performance:** Where a control retrofit is motivated by the opportunity to reduce energy consumption, cost effectiveness may be a key factor to consider.
- **Thermal Comfort Improvement**

This section provides guidance on considerations for screening existing buildings and systems for applicability and cost effectiveness and general lessons learned with applying G36 to existing buildings.

5.1 Data Collection and Screening

The goal of an initial screening is to determine if a building is suitable for G36 for retrofits driven by energy performance with a minimal amount of data collection. G36 covers a specific range of HVAC system types, so the first step in the process is to confirm that the candidate building HVAC system is covered by G36. The next step is to determine if the BAS infrastructure is capable of being re-programmed with G36 sequences or if a control hardware upgrade might be required. Figure 23 below summarizes this decision process.

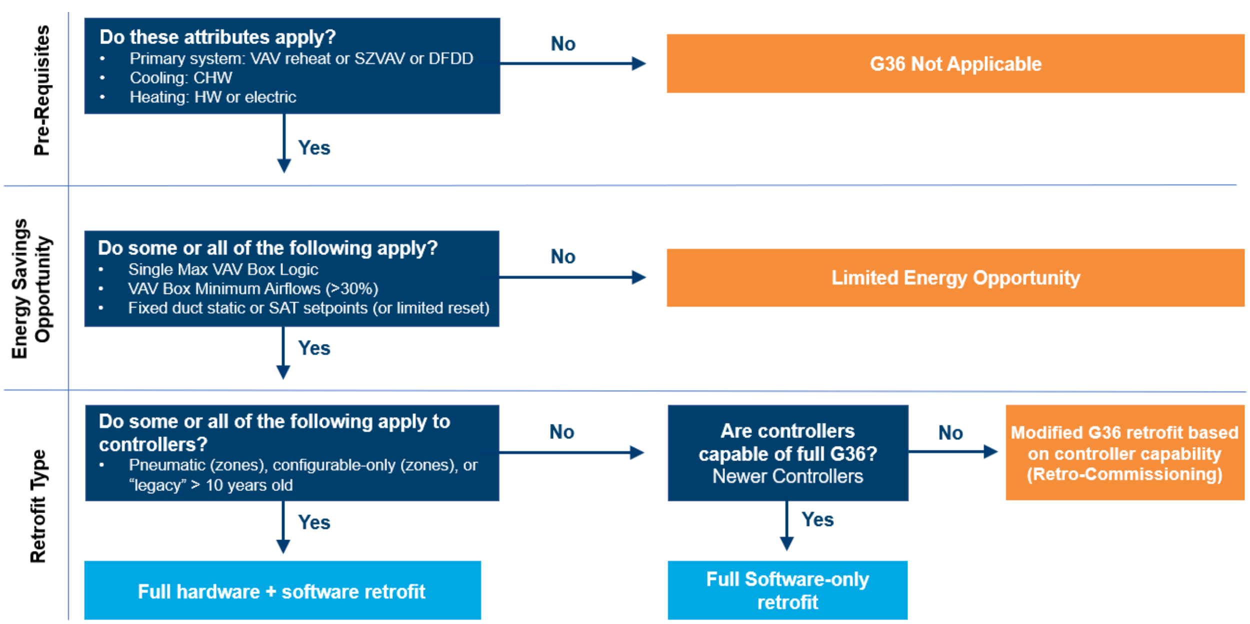


Figure 23. Identifying Opportunities for Guideline 36 Airside Control Retrofits

Collecting reliable information about the existing building systems is an essential, but often challenging, first step. Table 5 below provides suggested methods to obtain existing system design information, as well as the relative effort and data reliability for each method. The data is used to determine the HVAC systems as well as the energy savings potential.

Table 5. Suggested Methods to Obtain Existing BAS Information

Method	Effort/time involved	Reliability of Data	Notes
Interview Building Engineer	Low	Medium	Expertise varies and sometimes terminology varies
Interview controls technician or contractor/service provider who knows the building	Low	High	This person does not always exist
Obtain BAS graphics (screenshots), points lists, BAS design documentation (controls submittal)	Medium	High	Not always available
Get remote access to BAS	Medium to high	High	Requires setup and knowledge of unique BAS interfaces
Obtain original HVAC design drawings (that include equipment schedules), and drawings from retrofits that have occurred	Medium/high	Medium/high	Buildings with many retrofits are often poorly documented, documentation is often lost or incomplete

5.2 Energy Savings Opportunity

The opportunity for energy cost savings is highly dependent on the existing control system sequences of operation and setpoints. Factors that have a relatively large impact on energy use are listed below, and for each item the existing site data that is required for savings analysis is also indicated. These measures all assume a system that is basically functioning correctly—economizer measures will not save energy if the dampers are frozen, for example. When pursuing energy efficiency measures, it is important to first identify and address deferred maintenance issues; correcting existing system issues can often be a source of significant energy savings.

Table 6 and Table 7 below list control opportunities for air handling systems and for VAV zones, respectively. The opportunities in each table are ordered roughly from largest to smallest energy savings potential, based on the assumption of a typical office building.

Table 6. Air Handling System Control Opportunities

Attribute	Clear Savings Opportunity	Baseline Data Collection
Scheduling	If a building with a daytime occupancy pattern remains “on” all night long. This can occur even if a schedule is in place, if the schedule is incorrectly implemented.	Review schedules and verify that they are effective by reviewing operating status of AHU supply fans.
SAT setpoint (if fixed)	Yes	Review BAS graphics for existing SAT setpoint
SAT reset	If any of the following: • reset low limit >55F • reset high limit <65F • reset based on anything other than zone demand.	Review BAS graphics, programming and/or trends. What is reset based on (OAT, return air temp, zone demand, other)? What is the logic? What are the high/low limits for reset temperature?
DSP setpoint (if fixed)	Yes	Review BAS graphics for existing DSP setpoint
DSP reset	If reset low limit > 0.5” or reset based on anything other than zone demand.	Review programming and/or trends. What is reset based on (OA, zone demand, other)? What is the logic? What are the high/low limits for reset pressure?
Outdoor air control based on DCV	If system does not have DCV and/or OA flow is not modulated.	Review programming. If the building zones have DCV, does the OA intake modulate based on zone demand?
Outdoor airflow control	If outdoor airflow is maintained using a fixed minimum damper position.	Verify that outdoor damper is actuated and review outdoor airflow control scheme
Economizer high limit control	If using enthalpy control or if high limit deviates significantly from those in Title 24 or ASHRAE Std. 90.1	Review economizer airflow control scheme, high limit lockout type, and setpoint.

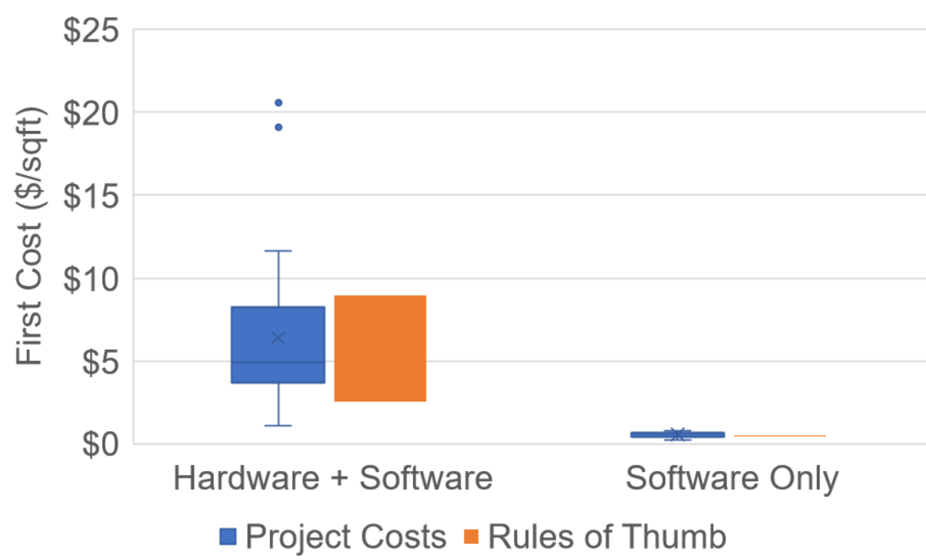
Table 7. VAV Zone Control Opportunities (for generic single duct VAV reheat)

Attribute	Clear Savings Opportunity	Baseline Data Collection
Pneumatic zone control	Yes, including the opportunity to replace old globe hot water control valves.	Observe existing zone thermostats.
Zone airflow sequence	If the SOO is single-max.	Review programming. Is the sequence: single-maximum, dual-maximum with DAT control, dual-maximum with reheat tracking heating loop output. Do the zones have DAT sensors?
Zone minimum airflow setpoint	If any of the following: • Minimum for interior zones is > 20%. • Minimum for west/south perimeter zones is > 10%.	Review design drawings schedule for minimum setpoints. Should be based on ventilation rate or controllable minimum. Existing setpoints often vary from design drawings. Calculate minimum flow as a percentage of maximum from BAS for a sampling of zones (interior and south/west perimeter zones separately).
Scheduling and Zone Groups	If any of the following: • Systems run for much longer hours than typical occupancy requires. • Occupants have varying schedules where a small proportion of occupants stay early or late and building is conditioned to match. • Zone Groups are not used to schedule groups of zones to match actual occupancy.	Talk to building engineer and review existing schedules. Does building have different occupancy/schedules across different areas of the building?
DCV (based on occupancy sensing)	If enclosed spaces do not have occupancy sensors for BAS control	Review programming. Determine if building uses occupancy sensing to setback ventilation and zone temperature setpoints.
DCV (based on CO2 sensing)	If > 20% of total ventilation airflow serves zones with DCV potential	Review design drawings. Calculate total area of potential DCV zones compared to total building area. Estimate fully occupied ventilation rate. Assess if building has potential for DCV zones (classrooms, conference rooms, etc.) that are not currently DCV. Current OSA flow setpoint (from TAB, or BAS)

Note that standard practice for estimating savings uses customized simulation, and spreadsheet analysis takes significant effort. One of the largest challenges is that baseline conditions are widely variable, as the tables above illustrate, and many of the tools/algorithms available do not accurately capture the dynamics of HVAC controls systems. Estimating the energy impact from faulty equipment and control is even more difficult, but addressing deferred maintenance issues often represents a significant portion of the overall savings that is achieved in real projects.

5.3 Cost Effectiveness

Cost estimating controls retrofits at this stage is very difficult, and cost per square foot estimates have high uncertainty. Contractor estimates should be used during project development. At the screening stage, estimating costs may be most appropriate based on the type of retrofit and floor area of retrofit. Normalized construction costs associated with G36 retrofits are shown in Figure 24 for both full control retrofits (hardware + software) and software-only retrofits. Cost data are based on project costs for the demonstration sites as part of the EPIC Best-in-Class project in California, as well as rules of thumb from various industry sources (27 data points for full control retrofits and 7 data points for software-only retrofits) from about 2015 to 2020. (Cheng, Singla, & Paliaga, 2022) Note that costs may be heavily dependent on project-specific conditions, differences in regional construction labor rates, construction market conditions, and the bidding nature for each project (negotiated vs competitively bid), among other factors.



(Cheng, Singla, & Paliaga, 2022)

Figure 24. Guideline 36 Retrofit Costs

5.4 Challenges with Guideline 36 Retrofits

Applying G36 in retrofits to existing control systems can be challenging for many reasons that are not applicable in new construction.

As-built HVAC documentation that is missing or incomplete. Mechanical schedules are generally needed to match design airflow setpoints in cooling and heating mode. With DDC systems, that information might be obtainable through the existing system, but systems with pneumatic zone controls may require new load calculations or as-found TAB surveys to determine airflow setpoints if reliable documentation is not available. Mechanical plans may be needed to calculate ventilation requirements for each zone and to determine new zone minimums. With incomplete or missing documentation, the project scope is difficult to define clearly and may require repeated interviews with building staff and field investigation. Often, small projects to add supplementary cooling or to modify room layouts are not documented clearly.

As-built BAS documentation that is missing or incomplete. A retrofit design should clearly identify the contractor scope and responsibility. For a retrofit of an existing building control system, the design should indicate what equipment, devices, and wiring can be retained, as well as what needs to be replaced and what needs to be installed new. Comprehensively understanding the existing control system inputs and outputs, devices, and original design intent are a key first step. Even in the best case, where control design schematics, existing system graphics, and existing system points lists are available, often there will be discrepancies that need to be investigated and reconciled. Though tedious, investigating and resolving these issues in design is generally much more cost effective than having change orders arise during construction.

Existing control hardware may not be compatible with G36. Though it covers a range of mechanical and control configurations, G36 is focused on best in class performance and new construction. Often the covered control options are not directly compatible with common existing control infrastructure. Demand for higher energy and ventilation performance has increased in the past several years, creating a widening gap in the functionality between existing building and new construction. Where there is a discrepancy between the existing functionality and G36, the designer must choose whether to make physical upgrades to match the control sequences in G36 or to adapt the sequence to work with existing conditions. The former may increase first cost and impact cost effectiveness, the latter may sacrifice some improvement in operational and energy efficiency. Requirements in G36 that are commonly incompatible with existing control systems include:

- **Active control of minimum outdoor airflow through an AFMS or differential pressure transducer.** Directly controlling measured outdoor airflow to maintain minimum ventilation is generally required by building codes, but longstanding conventional practice was to merely maintain a minimum damper position. This conventional approach is not capable of maintaining a consistent minimum ventilation rate for variable flow systems.
- **Independent control of outdoor, return, and exhaust air dampers.** For systems with relief fans, G36 controls the outdoor and return air dampers in sequence, rather in a complementary fashion as in common practice, to reduce pressure drop and fan energy. Where there is a dedicated minimum outdoor air damper, the return air damper is also modulated independently to maintain outdoor air flow at setpoint. For systems with return fans, G36 holds the outdoor air damper open continuously, and it only modulates the return air damper to maintain minimum ventilation and economizer temperature control. Typical practice is instead to have a single control output to all three dampers, which does not allow for independent control of each damper.
- **Control of return fans to track supply airflow or to maintain a discharge pressure setpoint.** G36 offers options to control returns fans via airflow tracking, which requires airflow monitoring stations in the return airstream or by maintaining the discharge pressure at setpoint. Though the former is not uncommon, fan speed tracking is generally more common. Revising existing

return fan control to match G36 often requires installation of one or more AFMSs or a differential pressure transducer.

- **Existing controllers may not be compatible with G36.** The control sequences in G36 are generally more complex than standard practice, requiring additional inputs and outputs (I/O), and more computations than is typical. Existing controllers may not have sufficient I/O capacity or memory to handle the G36 programming. Note that controller memory is often not a direct limitation, but rather, software limitations on the number of control blocks or points imposed by the manufacturers to maintain minimum acceptable performance. Existing configurable-only zone controllers are not capable of handling custom programming required by G36. As a particular sequence can be programmed to be more or less efficient or compact, with fewer or more blocks, and there are many different pathways within G36, there is generally not a simple way to determine upfront whether a controller is compatible with G36. Some features within G36 may be removed from scope to fit on existing controllers, but these simplifications may sacrifice performance.
- **Difficulty working in an existing building.** As with all retrofits, installing new devices and wiring can be more difficult and expensive. Working in an occupied building may require after-hours work, noise and staging limitations, more diligent cleaning, or phased work that may increase work complexity and cost.
- **Discovery of existing mechanical deficiencies and deferred maintenance.** Mechanical and control infrastructure have limited service lifespans. In many buildings, preventative maintenance and equipment renewal are not prioritized—it is common to find failed or failing equipment when doing work in existing buildings. Often thermal comfort and minimum ventilation are not maintained, but occupants have adapted and stopped complaining of discomfort. In particular, the ability to centrally monitor and alarm with DDC systems frequently uncovers many issues when upgrading from pneumatic control. Project stakeholders should expect to encounter and be asked to troubleshoot issues that may be out of scope. Common issues can potentially be anticipated and covered with unit pricing at bid to avoid change order pricing.

6

Operations and Troubleshooting

- Zone-level Issues
- System-level Issues

6 Operations and Troubleshooting

The operation of HVAC systems is critical to maintaining high performance with respect to energy efficiency and maintaining thermal comfort. Proper operation requires a concrete understanding of the mechanical and control system design intent. A well designed and implemented control system interface provides operators with a clear understanding of current conditions (through graphics, alarms, reports, etc.) and the ease of ability to make adjustments and overrides as necessary.

This section offers troubleshooting suggestions for a range of common issues that may be encountered with typical HVAC systems. For each issue, a list of recommended checks and actions is presented, as well as another list of actions that are not recommended (or that should only be executed with care to avoid unintended negative impacts to energy use and comfort). Recommendations are generally focused on controls-related issues with air-side equipment at the zone and system level. Note also that the recommendations are generalized. The range of potential HVAC system configurations is enormous, and applications can be widely variable. The recommendations presented here may not apply to all applications.

6.1 Zone-level Issues

6.1.1 Zone is Too Warm / "Stuffy"

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that zone airflow setpoint is maintained and that cooling max is at design value. If zone airflow setpoint is not maintained, see Section 6.1.3. 2. Confirm that SAT at AHU is maintained at or close to setpoint. If SAT setpoint not maintained, see Section 6.2.1. 3. Confirm that SAT setpoint at AHU is low enough to provide cooling. If SAT is reset above minimum, confirm that zone is generating requests (see Figure 22) and that T&R reset is responding appropriately. 4. Confirm whether measured space temperature is appropriate and representative of space conditions (e.g., is reading biased by solar exposure or behind a coffee maker). 5. Confirm that DAT at zone (if available) is equal to SAT from AHU (plus a few degrees for duct pickup). If DAT is significantly above SAT, there may be an issue with reheat control (if present). 6. Confirm that the zone cooling temperature setpoint is set appropriately within normal design range. For typical comfort applications, design space cooling temperatures generally range from 73 to 77°F. Cooling setpoints below this range may not be consistently achievable due to cooling capacity limitations. 7. If zone is frequently too warm, consider increasing maximum cooling airflow setpoint (not overriding the current airflow setpoint) on the VAV control graphic to increase maximum cooling capacity. Note, this may increase noise at diffusers. 8. Consider personal comfort system, like a low-cost small desk fan. 9. Check for manual overrides that may have been inadvertently left in place.	1. Do not override the airflow setpoint: Doing so may increase airflow to the zone indefinitely. The hot call may be a transient issue whereas a setpoint override may be forgotten and left in place. If the temperature is above the zone cooling temperature setpoint, the control loop should automatically raise airflow setpoint toward the cooling max airflow limit. 2. Do not increase zone minimum, this increases airflow (and energy use) when in deadband. If zone is too warm, the zone should be in cooling mode where the zone minimum setpoint has no impact. 3. Do not lower zone cooling setpoint beyond the normal design range. If system is already unable to maintain the temperature at the design value, lowering the setpoint will not improve conditions and may lead to other unintended issues. 4. Do not override the reheat coil off or shut. Doing so may lead to the coil be inadvertently disabled indefinitely and prevent the system from providing heat in the future when needed. 5. Do not fix the AHU SAT setpoint to minimum. Doing so will significantly increase energy consumption and the override may be left in place indefinitely. 6. Do not override the AHU supply fan speed. If zone airflow setpoint is not maintained, see Section 6.2.1.

6.1.2 Zone is Too Cold

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that reheat coil is active and providing heat (DATs greater than room temperature). If not, see Section 6.1.4 for issues with maintaining DAT at setpoint. 2. Confirm that zone heating and cooling setpoints are set appropriately (e.g., cooling setpoint is not set too low). 3. Confirm that zone temperature heating loop is fully wound up. If loop signal is less than ~90%, zone is not yet in full heating. Examine VAV control logic and control loop tuning/gains to determine why heating loop is not responding to cold conditions. 4. Confirm that zone minimum airflow setpoint is not too high. Zone minimums should generally be set to no more than 15-30% of the cooling maximum, where higher minimums may result in overcooling. 5. Confirm that DAT and/or setpoint is not too high. With DATs that are more than 15 to 20°F above ambient room temperature, the buoyancy of the hot air may lead to stratification, preventing the hot air from mixing into the space and providing effective heating. Energy and ventilation codes limit this temperature difference to 20°F. 6. If zone is too cold in the morning, confirm that Warmup mode operated correctly and that optimum start commenced with enough time for the coldest zones to recover by the start of occupied mode. Ventilation need not be provided during Warmup mode; operation with recirculated return air only during Warmup may reduce energy use, shorten the recovery time, and reduce the risk of overcooling zones without reheat coils. 7. Consider personal comfort system, like a heated footrest or chair. 8. For cooling only zones, ensure minimum is not too high, ensure SAT setpoint is reset effectively. 9. Check for manual overrides that may have been inadvertently left in place.	1. Do not increase DAT setpoint to more than 20°F above the zone heating setpoint. When the DAT is significantly higher than the room temperature, the buoyancy of the hot air may cause it to stratify and prevent mixing with room air. This stratification may cause the hot air to short circuit back to ceiling return grills and result in a net decrease in heating capacity. 2. Do not increase zone heating setpoint above 72°F. If system is unable to maintain current heating setpoint, increasing the setpoint will not improve the situation and may cause other unintended issues. 3. Do not override hot water temperature setpoint. Doing so may lead to the setpoint being fixed indefinitely, which wastes energy. If setpoint reset is resulting in low setpoints, confirm that zone is generating hot water temperature requests (if applicable). 4. Do not increase zone heating airflow limit above design value or above 50% of cooling maximum. Increasing the airflow too high may reduce the DAT and decrease the effective capacity of the reheat coil to add heat to the space (a larger fraction of the coil capacity would be used to warm the primary air up to neutral room temp instead).

6.1.3 Zone Airflow Not Maintained at Setpoint

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that zone damper is commanded fully open. 2. Confirm that associated supply fan is operational and maintaining duct static pressure at setpoint. See Section 6.2.3 if DSP not maintained at setpoint. 3. Confirm that airflow setpoint does not greatly exceed design value. Increased pressure drop may limit the equipment's ability to provide higher airflows above the design limits. 4. If damper is fully open, confirm that zone is generating pressure requests to indicate demand for more pressure (see Figure 22) and that they are received at the AHU. If system duct static pressure setpoint is below maximum and not increasing, consider reducing the number of ignores in the T&R reset at the AHU or increasing the Importance multiplier for this zone (doing so may increase fan energy) (see Section 3.2.5). 5. Confirm that the static pressure request importance multiplier is not set to zero. 6. Confirm that zone damper is physically open, and that the actuator is securely attached to damper shaft. 7. Check for manual overrides that may have been inadvertently left in place.	1. Do not increase zone airflow setpoint. If the system already cannot achieve the current airflow setpoint, further increasing the setpoint will not improve conditions, but it runs the risk of creating control issues if override is left indefinitely. 2. Do not override zone damper position. If the zone damper is already fully open and not maintaining airflow setpoint, overriding the damper position will not improve conditions, but it runs the risk of causing control issues if override is left indefinitely. 3. Do not override duct static pressure setpoint. Doing so runs the risk of unnecessarily increasing fan energy use if override is left indefinitely.

6.1.4 Zone Discharge Air Temperature Setpoint is not Maintained

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that the maximum DAT setpoint is set no higher than the design coil leaving air temperature. 2. Confirm that the heating maximum airflow setpoint is not too high, and not higher than the coil design airflow. Energy codes limit reheat airflow to no more than 50% of the cooling maximum. Higher airflow rates may result in excessive wasted energy. More importantly, higher airflows across a reheat coil may result in lower DATs and less heat being added to the space (because more of the heating capacity is spent on reheating the primary air). 3. If there is a hot water reheat coil, confirm that the control valve is commanded fully open. 4. If there is a hot water reheat coil, confirm that isolation and balance valves are open, and control valve is physically open. 5. If there is a hot water reheat coil, confirm that boiler plant is enabled and providing hot water (temperatures are hot enough and pumps are running). 6. If there is a hot water reheat coil and hot water temperature setpoint is reset based on zone demand, confirm that zone is generating HHW supply temperature requests to indicate demand for higher temperature water (see Figure 22). If HHW supply temperature setpoint is below maximum and not increasing, confirm that T&R reset is responding appropriately (see Section 3.2.5). Consider reducing the number of ignores in the T&R reset at the hot water plant or increasing the Importance multiplier for this zone. 7. If there is a hot water reheat coil and hot water temperature setpoint is reset based on OAT, consider adjusting limits to provide warmer hot water temperatures. Also consider revising control to use demand-based setpoint reset. 8. If there is an electric reheat coil, confirm that duct heater is operational (e.g., not tripped or disabled due to low flow). 9. If there is a hot water reheat coil located at a high point in the hot water loop, bleed air to ensure the coil is not vapor locked. 10. Check for manual overrides that may have been inadvertently left in place.	1. Do not override DAT setpoint. Doing so may lead to the setpoint being inadvertently fixed indefinitely and overheating the zone in the future. 2. Do not override the hot water valve or reheat coil output command. Doing so may lead to the valve locked open indefinitely and overheating the zone in the future. 3. Do not override hot water temperature setpoint. Doing so may lead to the setpoint being inadvertently fixed indefinitely, and which wastes energy. If setpoint reset is resulting in low setpoints, confirm that zone is generating hot water temperature setpoint reset requests (if applicable).

6.2 System-level Issues

6.2.1 Supply Air Temperature Setpoint is not Maintained in Cooling

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that the minimum SAT setpoint does not exceed its design value. 2. Confirm that the outdoor air and return air dampers physically correspond with their commanded positions. 3. In hot weather, confirm that the outdoor air fraction does not exceed the design. 4. If CHW, confirm that the CHW control valve is commanded and physically open. 5. If CHW, confirm that coil isolation valves are open. 6. If CHW, confirm that CHW plant is enabled, producing cold water, and that pumps are on. 7. If CHW, confirm that AHU is generating both CHW supply temperature setpoint reset requests and also plant run requests, to indicate demand for higher temperature water and to ensure that the CHW plant is enabled (see Figure 22). If CHW supply temperature setpoint is above minimum and not decreasing, consider reducing the number of ignores in the T&R reset at the hot water plant or increasing the Importance multiplier for this AHU (see Section 3.2.5). 8. If cooling is by DX, confirm that compressors are enabled. If not confirm whether a safety has been tripped, airflow exceeds minimum flow requirement, or the presence of any other faults. 9. If there is an airside economizer, confirm that economizer high limit is appropriately set to lock out the economizer when the outdoor conditions are unfavorable (e.g., too warm), and that physical damper operation matches the BAS command. 10. If the CHW coil is located at a high point in the CHW loop, bleed air to ensure the coil is not vapor locked. 11. Check for manual overrides that may have been inadvertently left in place.	1. Do not override or fix the SAT setpoint. 2. Do not override the hot water or CHW valve commands. Doing so runs the risk of overheating/overcooling zones and increasing fan energy. 3. Do not override the CHW supply temperature setpoint. Doing so may lead to the setpoint being inadvertently fixed indefinitely, which wastes energy. 4. Do not disable the air side economizer or override the outside air damper shut.

6.2.2 Supply Air Temperature Setpoint is not Maintained in Heating

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that the maximum SAT setpoint does not exceed its design value. 2. Confirm that the outdoor air and return air dampers physically correspond with their commanded positions. 3. In cold weather, confirm that the outdoor air fraction does not exceed the design. 4. If there is a hot water coil and SAT is below setpoint, confirm that the hot water valve is commanded and physically open. 5. Confirm that coil isolation valves are open. 6. If there is a heating coil, SAT is below setpoint and the hot water valve is fully open, confirm that AHU is generating both HHW supply temperature reset requests and also plant run requests, to indicate demand for higher temperature water and to ensure the hot water plant is enabled (see Figure 22). If HHW supply temperature setpoint is below maximum and not increasing, consider reducing the number of ignores in the T&R reset at the hot water plant or increasing the Importance multiplier for this AHU (see Section 3.2.5). 7. If the hot water coil is located at a high point in the hot water loop, bleed air to ensure the coil is not vapor locked. 8. Check for manual overrides that may have been inadvertently left in place.	1. Do not override or fix the SAT setpoint. 2. Do not override the hot water or CHW valve commands. Doing so runs the risk of overheating/overcooling zones and increasing fan energy. 3. Do not override the hot water supply temperature setpoint. Doing so may lead to the setpoint being inadvertently fixed indefinitely, and energy waste. 4. Do not disable the air side economizer or override the outside air damper shut.

6.2.3 Duct Static Pressure Setpoint is not Maintained

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that the supply fan variable speed drive is in auto and is not in alarm or faulted. If there is a fan array, check for failed fan motors. 2. Confirm that the supply fan variable speed drive responds to the control signal from the BAS. 3. Check that maximum fan speed is not limited to less than the design speed. 4. Confirm that maximum duct static pressure setpoint is not set too high. Upper limit should generally be determined by test and balance to achieve design system airflow. Increasing the limit to a higher value as needed may be appropriate but doing so may result in conditions that potentially exceed fan capacity. 5. Confirm that the duct static pressure sensor is working properly—check that duct static pressure sensor reading responds to changes in fan speed. 6. Confirm that SAT setpoint is not reset too high. To meet a given cooling load, warmer SATs require more airflow. SATs should generally be reset upward during periods of low to moderate cooling load, but an aggressive reset strategy (e.g., with high setpoints or setpoint limits) may result in conditions with high airflows that exceed the fan capacity. 7. If there is a return fan, confirm that return fan is operational and controlled effectively (e.g., tracking supply fan and/or maintaining return fan discharge plenum at slight positive pressure), otherwise supply fan may be overtaxed with additional duty of “pulling” return air back to AHU. 8. Confirm that there are no large duct leaks. 9. Confirm that most or all VAV box dampers are not fully open. If most or all of the dampers are fully open (e.g., during Warmup Mode), the supply fans will not be able to build up enough static pressure. 10. Check for manual overrides that may have been inadvertently left in place.	1. Do not override the fan speed signal as this can lead to over/under pressurization of the ductwork and increased fan energy if left in this condition. 2. If there is additional motor capacity and conditions do not exceed the fan class, fans can be resheaved or motors overspeeded to provide additional pressure.

6.2.4 Supply Air Temperature or Duct Static Pressure Setpoint is cycling excessively

T&R resets will typically oscillate with a full cycle period of about an hour as the resets seek a balance point with the building load. Reset behavior may be considered excessive if there are repeated swings from the minimum to the maximum, where the setpoint trims and responds at the maximum rate possible.

Recommended Actions	Not Recommended (or proceed with care)
1. Investigate whether there is a single rogue zone that continually dictates when the setpoint trims or responds. If so, that zone may need attention to address any operational issues and prevent it from driving the system-level reset. 2. Consider adjusting the trim value to slow the rate at which the setpoint is trimmed at each time step. 3. Investigate whether interactions between plant and AHU-level resets may be causing the excessive cycling and require further tuning. 4. Consider increasing the number of ignores. Increasing the number of ignores delays the system from responding until there is more demand (i.e., more requests). This may reduce energy consumption and help provide stability, but at the potential cost of not maintaining comfort at the first zones whose requests are not satisfied.	1. Do not override the SAT/DSP setpoint as this will likely result in an increase in energy or thermal comfort issues.

6.2.5 Supply Air Temperature or Duct Static Pressure Setpoint is not resetting

Recommended Actions	Not Recommended (or proceed with care)
1. Confirm that the number of ignored requests is set less than the total number of requests. 2. Confirm that the trim and respond parameters are set correctly, using the correct signs, as listed in G36. For SAT setpoint trim and respond, the trim by term should be set to a positive number, while the respond by term should be set to a negative number. For duct static pressure setpoint trim and respond, the trim by term should be set to a negative number, while the respond by term should be set to a positive number. 3. If the setpoint is pegged at its minimum value (for cooling SAT trim and respond) or maximum value (for duct static pressure trim and respond), investigate zones that are generating the most requests and resolve zonal issues. See Sections 6.1.1 and 4.5.5.	1. Do not override the SAT/DSP setpoint as this will likely result in an increase in fan energy and will result in additional zonal comfort issues.

7 Educational Resources for Advanced HVAC Controls and Guideline 36

7.1 Trainings and Seminars Available Online

BEST Center 2020 Annual Institute: "ASHRAE Guideline 36 – High Performance Sequences of Operation for HVAC Systems"

Steve Taylor (Taylor Engineers) presented a seminar for the Building Efficiency for a Sustainable Tomorrow (BEST) Center at Laney College in 2020. The training and lab demonstration were recorded and posted online here:

https://www.youtube.com/watch?v=g2bvUCDKGEU

https://www.youtube.com/watch?v=flxaJWouAVw

AMCA insite Webinar: "VAV Systems Part 1: VAV Design Tips"

Steve Taylor (Taylor Engineers) presented a webinar for the Air Movement and Control Association (AMCA) insite webinar series in 2021. The webinar is available online here:

https://amca.wistia.com/medias/mrwuppyiw4

ASHRAE Hawaii Chapter Meeting: "Guideline 36: Best in Class HVAC Control Sequences"

Steve Taylor (Taylor Engineers) presented at the January 2021 ASHRAE Hawaii Chapter meeting. The recorded meeting is available online here:

https://public.3.basecamp.com/p/cpu2bisnAAnLxC5mTnidc1AY

7.2 Trainings

ASHRAE Instructor-Led training

Since 2018, ASHRAE has offered live seminars titled "Guideline 36: Best in Class HVAC Control Sequences". These have typically been three-hour classes, offered two times per year alongside the Winter and Summer ASHRAE meetings.

Find out information about upcoming classes through the ASHRAE Learning Institute and through the ASHRAE Conference course listings:

https://www.ashrae.org/professional-development/all-instructor-led-training/instructor-led-training-seminar-and-short-courses

https://www.ashrae.org/conferences

https://www.ashrae.org/professional-development/all-instructor-led-training/instructor-led-training-seminar-and-short-courses/guideline-36-best-in-class-hvac-control-sequences

PG&E Energy Centers

The PG&E Energy Centers have periodically offered live classes on G36 or advanced HVAC controls. These have typically been eight-hour classes, offered sporadically since 2018. Classes are free of charge and are generally available in an online webinar format.

Find out information about upcoming classes here: https://www.pge.com/en_US/small-medium-business/business-resource-center/training-and-education/energy-centers.page?ctx=large-business

7.3 Reference Documents

ASHRAE Guideline 36-2021 High Performance Sequences of Operation for HVAC Systems

https://www.techstreet.com/standards/guideline-36-2021-high-performance-sequences-of-operation-for-hvac-systems?product_id=2229690

Fundamentals of HVAC Control Systems, by Ross Montgomery and Robert McDowall. 2011. ASHRAE Learning Institute.

This book provides a thorough introduction and a practical guide to the principles and characteristics of HVAC controls. It describes how to use, select, specify, and design control systems.

https://www.techstreet.com/ashrae/standards/fundamentals-of-hvac-control-systems-i-p?gateway_code=ashrae&product_id=1771686

Advanced Variable Air Volume System Design Guide. Energy Design Resources. Pacific Gas and Electric Company. Second Edition. March 2007.

The Advanced Variable Air Volume System Design Guide is written for HVAC designers and focuses on built-up VAV systems in multi-story commercial office buildings in California.

https://tayloreng.egnyte.com/dl/jzNGKhmF1C/EDR_VAV_Guide.pdf_

See also the list of references in Chapter 8.

7.4 Other Resources

Building Operator Certification

Building Operator Certification® is the leading training and certification program for building engineers and maintenance personnel.

https://www.theboc.info

ASHRAE Standing Guideline Project Committee 36 Website

http://gpc36.ashraepcs.org/index.php

8 References

Arens, E., Zhang, H., Hoyt, T., Kaam, S., Goins, J., Bauman, F., . . . Torftum, J. (2015). *RP-1515 -- Thermal and Air Quality Acceptability in Buildings that Reduce Energy by Reducing Minimum Airflow From Overhead Diffusers.* ASHRAE.

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