Field Demonstration of an Automated Building Commissioning Tool

Hayden Reeve, PhD
Member ASHRAE

Buyun (Jason) Jing

Zhengang Zhu

Rohan Chabukswar, PhD

Anarta Ghosh, PhD

Yun Li

ABSTRACT

Commissioning is important for ensuring that buildings operate efficiently and provide satisfactory occupant comfort and productivity. Unfortunately, commissioning building systems can be labor intensive, limiting how widely and often it is performed. This paper presents an automated commissioning tool for the testing of variable air volume (VAV) terminal units. Multiple field demonstrations are presented including one of the tallest skyscrapers in Asia. Results found that an average 13% of VAVs had pre-existing faults. The scalability and labor savings of the method are discussed along with the resulting improvements in building energy performance and air quality.

INTRODUCTION

Buildings have a significant impact on operating costs for businesses as well as on occupant health and the environment. For example, in the U.S. alone, building owners spent $432 billion on energy in 2011, which is equivalent to what U.S. businesses spent on health care and more than what they spent on payroll taxes (Rhodium Group, 2013). In addition, commercial buildings contributed 18 percent of overall carbon emissions within the U.S. (U.S. Energy Information Administration, 2011). Intelligent and integrated building systems can provide significant benefits in these areas, including reducing energy consumption (Romano, 2015). They can also improve occupant comfort and productivity. However, to ensure high performance of these systems, it is important that such systems are installed and tuned correctly, and faults that occur are addressed through re-commissioning or continuous commissioning (also known as monitoring-based commissioning). A report by the Department of Energy (Baechler and Farley 2011) noted that: (1) the commissioning process can reduce total construction costs by an estimated 4 to 9 percent and (2) in a study of 60 commercial buildings: over 50 percent suffered from control problems; 40 percent had problems with HVAC equipment; 33 percent had sensors that were not operating properly; and 15 percent were missing specified equipment. Cities such as Seattle and New York now require commissioning and retro-

Hayden Reeve is an associate director at United Technologies Research Center, East Harford, CT. **Buyun (Jason) Jing, Zhengang Zhu, and Yun Li** are research scientists at United Technologies Research Center, Shanghai, China. **Rohan Chabukswar and Anarta Ghosh** are research scientists at United Technologies Research Centre, Cork, Ireland.

commissioning of commercial buildings.

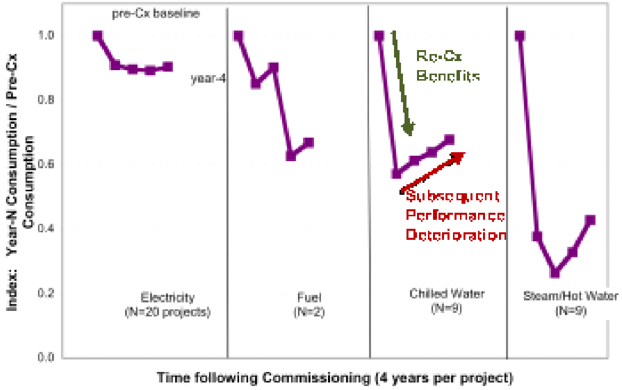

Figure 1 Benefits from building commissioning can soon be lost due to subsequent deterioration (Mills 2004).

The energy and cost savings of building commissioning and associated building diagnostics tools have been extensively studied. Lawrence Berkeley National Laboratory (LBNL) has shown the benefits of building commissioning (Cx), with median energy reductions of 16% for existing buildings (Mills 2009). In 24 Californian buildings reviewed by LBNL as part of an evaluation of the impact of building diagnostics, benefits ranged from 2-25% building-level energy savings with a mean energy cost savings of $0.25 per square foot per year (Mills et al. 2009). Despite these benefits, performance can soon start to degrade again (Mills 2004) (see Figure 1), showing the need for commissioning and tuning tools that are automated, provide actionable recommendations and can be run on an ongoing basis. In specific examples, building diagnostics have been implemented by Microsoft on 13 buildings (2.6 million sq. ft.) as part of a smart building pilot that included data aggregation, analytics and visualization. Their experience demonstrated that smart building solutions can reduce energy consumption by 6-10% and be installed for less than 10% of annual energy consumption with an expected payback of less than two years (Cook 2012). In another example, Hunan University implemented diagnostics on 1,186 VAVs in the 317,361 sq. ft., 36-story Cambridge House office building in Hong Kong, resulting in a 13% decrease in annual cooling electrical load (Chen et al. 2014). HVAC energy savings can only occur in cases where the VAV box heat was stuck on and active or the damper is stuck open. In many cases, if the box fails to provide the necessary airflow, it will reduce energy consumption but cause occupant discomfort.

In addition to energy savings, identifying and optimizing HVAC equipment operation can greatly improve indoor air quality, especially carbon dioxide (CO_2) levels. High CO_2 levels in buildings have been associated with lost productivity and a range of health issues. In field studies, insufficient ventilation (and higher CO_2 levels) has been found to decrease productivity of call centers by 6% (Wargocki et al. 2004) and negatively impact classroom test taking (Wargocki et al. 2007). Field studies in North America have shown inadequate ventilation resulting in a 50% increase in employee sick days and an economic impact of $400 per year per employee (Milton et al. 2000). A field study in New Delhi, India, found that higher CO_2 levels, in combination with other factors such as stress and computer work, increased the occurrence of symptoms such as headaches and lethargy (Gupta et al. 2007). LBNL has shown that even CO_2 levels of 1,000 ppm statistically reduce the performance of strategic thinking and decision making (Satish et al. 2012). A recent study by Harvard (funded by United Technologies Corporation) showed superior ventilation improved occupant cognitive function and productivity (Allen et al. 2016). In this study, 24 participants spent six full work days in an environmentally controlled office space, blinded to test conditions. Cognitive function test scores were 15% lower for the test day with moderate CO_2 levels (~ 945 ppm) and 50% lower on the day with CO_2 concentrations of ~1,400 ppm than on the two days with low CO_2 levels (~485 ppm and ~586 ppm). Such gains in occupant health and productivity provide additional value that can far exceed those provided by energy savings alone.

Traditionally, the HVAC inspection portion of the commissioning process is manual and often prohibitively labor intensive, reducing the likelihood it is conducted on all equipment, let alone repeated often. Numerous approaches have been developed with the goal of ensuring that these Cx savings persist over time. A practical guide for building commissioning was developed by the Department of Energy (DOE) in 1999 (Haasl and Sharp 1999). Most processes presented in this guide focus on bringing building operation to the original design intent through maintenance actions. Fault detection and diagnostic (FDD) technologies are the primary requirement for such Cx processes. There have been numerous FDD methodologies developed for systems and components of building HVAC systems in this context (Jenkins and Brook 2003; Katipamula and Brambley, 2005a; Katipamula and Brambley, 2005b; Kim and Katipamula 2017). Texas Engineering Experiment Station's Energy Systems Laboratory at Texas A&M University developed a different approach, viz., continuous commissioning methodology, which focused on optimizing HVAC system operation and control for the building conditions, and was demonstrated in 130 buildings, achieving average measured utility savings of 20% with paybacks often in less than 2 years (Liu et al. 1994; Claridge et al. 1994; Liu et al. 1999, Claridge et al. 2000).

To achieve broad deployment of such solutions and the resulting benefits, tools need to overcome a range of challenges. First, mapping the required building data to the algorithms can be labor intensive, requiring approaches for automated data mapping. Furthermore, methods need to determine the building equipment's pre-existing health status versus simply detecting anomalies from baseline patterns. Finally, the results of diagnostics tools need to be accurate to reduce false alarms that could cause findings to be ignored, and to reduce the need for external subject matter experts to review data prior to making recommendations to facility managers.

This paper presents an automated commissioning tool that focuses on greatly reducing the labor of verifying the functional performance of VAV terminal units. This approach is also applicable to other types of terminal units (e.g., fan coil units), provided the required instrumentation is present. Terminal units are targeted for automated testing due to their large number, distributed locations and the difficulty in accessing them. The remainder of this paper will provide an overview of the technical approach, followed by an overview of four global field demonstration sites where this tool was tested. Finally, a discussion of the number and nature of VAV faults and the observed benefits is provided.

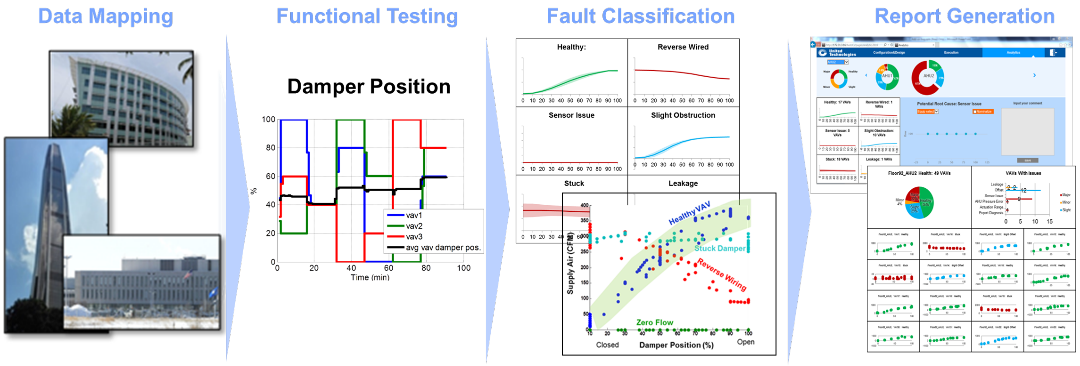

Figure 2 The automated commissioning tool for airside terminal units comprises four major steps.

APPROACH

The automated commissioning tool (ACT) deployment process is shown in Figure 2. The tool is an add-on to the WebCTRL® building automation system (BAS) or can be deployed as an overlay on other vendors' BAS. Once installed, a number of highly automated engines are executed that address the common challenges encountered when performing diagnostics of building HVAC systems. First, a data-mapping engine automatically determines the number and topology of air handling units (AHUs) and VAVs on site and then identifies and maps the required data-points.

Next, automated functional tests are designed and conducted concurrently on all the VAVs in the building. The tests run over the course of 90 minutes and use optimum scheduling algorithms to avoid overloading of AHUs and VAVs.

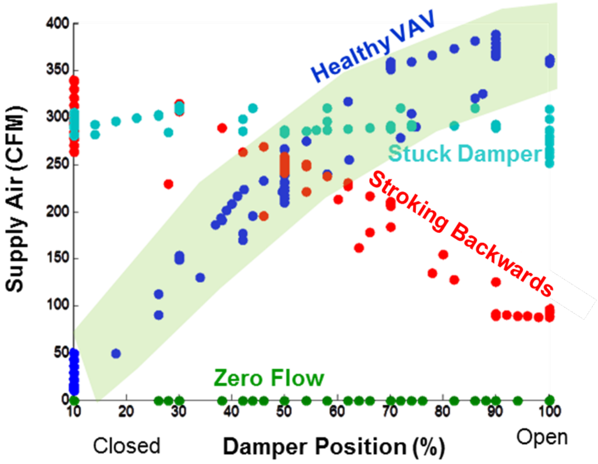

Figure 3 Example of actual functional test results for VAV damper performance. Healthy VAV operation is shown (navy blue), in comparison to a VAV that fails to communicate (green), is stroking backwards (red), or stuck (light blue).

The data generated by these tests are analyzed based on the known physical behavior patterns and faults of VAVs, such as "stuck" or "stroking backwards" dampers, as shown in Figure 3. For detailed VAV damper fault analytics, parameters of a physical model relating damper position (x) to airflow (Q), shown in Equation 1, are estimated from the functional test data. The parameters of this model capture the fault modes, e.g., α corresponds to resistance ($\alpha > 0$), β corresponds to leakage ($0 \leq \beta \leq 1$); and ϕ corresponds to angular offset ($-\pi 2 < \phi \leq \pi 2$). The values of these parameters are then used to classify the VAV performance into various health categories (e.g., healthy, stuck, stroking backwards). Terminal units whose performance cannot be classified into these categories are designated to require human diagnosis.

$$Q = A * \sqrt{\frac{1+\frac{1}{\alpha}}{1+\frac{1}{\alpha\left(\beta+(1-\beta)*\left(1-\left|\cos\left(\max\left(\frac{x}{100}*\frac{\pi}{2}+\phi,0\right)\right)\right|\right)\right)^{2}}}} \qquad (1)$$

As the next step in the process, VAVs with similar faults are clustered together and a report of the health condition of all VAVs is automatically generated noting the specific faults. This avoids inundating operators with the laborious and time-consuming manual tasks of detecting and analyzing hundreds of faults and alarms. Once completed, and any pre-existing faults are fixed, the ACT can be rerun on an ongoing basis providing a report for facilities management to take specific maintenance actions to ensure continuous optimum building HVAC performance.

FIELD DEMONSTRATION

The ACT has been field demonstrated on commercial buildings at a number of international sites. These sites cover a wide range of use cases from verifying initial equipment installation to ensuring on-going system health and supporting whole building retro-commissioning. The field demonstration sites include buildings in Asia, representing both mega-tall buildings and modern LEED-certified buildings, as well as North America, representing existing building stock. Given this range of use cases and building sites, a common measurement and verification strategy (and associated performance metrics) could not be implemented. Therefore, a range of quantitative and qualitative results is presented below, illustrating the range of benefits experienced as a result of these demonstrations. The number and types of VAV faults are reported for all sites.

Figure 4 Summary of field demonstration sites: (A) Asian Skyscraper; (B) Indian Office Building; (C) North American Office Building 1; and (D) North American Office Building 2.

Summary of Field Sites

Site A: Asian skyscraper. The ACT was used to verify the initial installation of VAV terminal units at one of the tallest skyscrapers in Asia. The building has over 110 floors and approximately 200 AHUs and 10,000 VAVs, making manual inspection and verification of all units' performance immensely labor intensive. The ACT was used to verify the performance of 4,788 VAVs during the initial building commissioning.

Site B: Indian office building. This is a 200,000 sq. ft., seven-story office building that is cooled by two heat recovery wheels that feed 14 AHUs. These, in turn, deliver cool air to 218 VAV terminal units. The climate does not require heating and, consequently, no boiler or reheating coils are present. This building is certified LEED Platinum. The functional tests were applied to this building as part of a demonstration of the ACT process. The results are included here as an additional example of the VAV fault rate and resulting benefits that can be achieved by the ACT process for a modern LEED certified building.

Site C: North American office building 1. This is a three-story office building located in Connecticut. It is cooled by six AHUs and 260 VAV terminal units. The ACT was demonstrated on site in support a 2017 retro-commissioning effort. The tool was run after test and balance was completed on the building and rerun to verify the resolution of identified VAV faults after repairs had taken place.

Site D: North American office building 2. This is a three-story office building located in Connecticut. It is cooled by nine AHUs and 281 VAV terminal units. The ACT was demonstrated on site in support of an on-going service contract provided by the building automation system vendor.

Automated Commissioning Results

Summary of VAV faults: A summary of the major VAV faults found at each site are provided in Table 1. For this study only, dampers that are stuck, stroke backwards, have sensor or communication issues (for example, reporting negative or identically zero airflow), or require expert diagnosis are reported. While the tool does identify VAVs that may have leakage, are over or under stroking, or may have obstructions, these minor faults may not sufficiently comprise a VAV's functional performance to warrant repair or tuning. Ground truth data for all VAVs could not be generated due to the time it would take to inspect all VAVs. As such, a complete analysis of the performance of the algorithms (detection rate and false alarm rate) was not possible. However, of the inspected VAVs identified to be faulty, almost all were found to have issues that required action. For example, at Site C, out of the 37 VAVs inspected, only one was considered to be healthy (false alarm). It is expected that the diagnostics performance will improve as data from more field sites is analyzed and algorithm thresholds are refined. Examples of the types of issues found during manual inspection are described in the subsection below.

Table 1. Identified Major Faults by Site

Site	Total Issues	Stuck	Stroking Backwards	Sensor & I/O	Expert Diagnosis Required
A	640 (13%)	250 (5%)	3 (<1%)	387 (8%)	-
B	48 (22%)	27 (12%)	2 (<1%)	19 (9%)	-
C	44 (17%)	28 (11%)	11 (4%)	5 (2%)	2 (<1%)
D	6 (2%)	5 (2%)	0 (0%)	1 (<1%)	0 (0%)

Inspection effort benefits: The primary benefit of the ACT is the substantial reduction in time and labor taken to inspect terminal units. The inspection benefits stem from three main features. First, the use of ACT does not require a site visit. The required control logic changes, tool installation and test execution can be conducted remotely. In addition, the test can be scheduled to run during unoccupied hours minimizing any disruption to occupants. This greatly reduces the required labor and leads to the second benefit: testing can be executed on all terminal units – not just a statistical sampling. It is not uncommon for current methods to inspect a sample of terminal units (for example, 10-20%) and only inspect all units if the fault rate on the initial sample exceeds a threshold (for example, 10%). Once initial installation and mapping are complete, testing can be applied to all units and rerun as required with only minimal effort. When executed on Site A, the use of the ACT substantially reduced the time it took to verify the performance of >4,800 VAVs from an estimate of weeks or months to a matter of days.

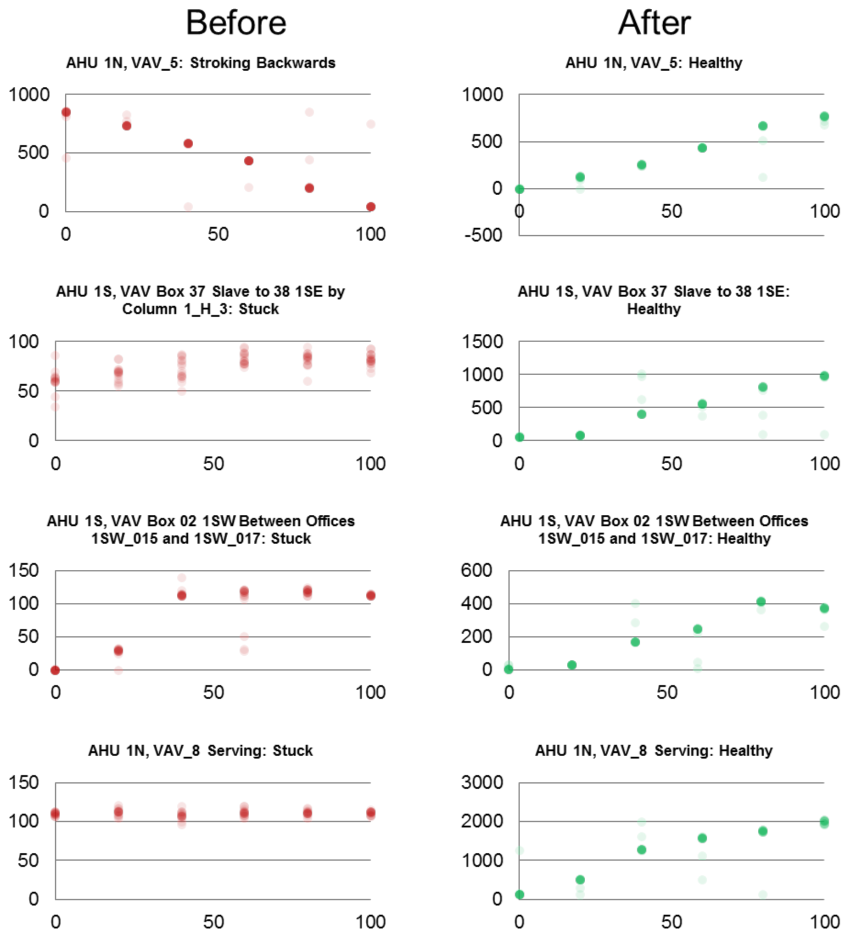

Figure 5 Comparison of VAV performance results for Site C before and after fixing identified faults. (Note varying vertical scales.)

Resolution verification benefits: In addition to the improved speed and reduced labor to determine faults, the ACT report provides performance summaries and fault classifications for each VAV. This has three key benefits. First, it provides users with the likely fault, making it easier to determine delegation of responsibility and course of action before a manual inspection of the damper. Second, the inclusion of performance data plots (such as those shown in Figure 5) allows users to independently determine the VAVs condition, building trust in the classification results and allowing rare misclassifications to be identified before traveling on site. Finally, the tests and reports can be rerun after VAVs have been fixed, providing verification to building operators that all equipment is functioning correctly. Examples of VAV performance plots for Site C are shown in Figure 5. "VAV_5" (Figure 5, top) shows reverse stroking behavior before resolution and healthy behavior after the controller's stroke was reversed and the air station was re-zeroed. VAV "Box 37" shows stuck behavior before resolution and healthy behavior (and a 10X increase in flow) after the controller was power cycled. "Box 02" was classified as stuck. On-site inspection found that its air balance damper was closed. After this was addressed and the controller was power-cycled, the VAV tested as healthy and provided almost four times the flow. Finally, VAV 8 was classified as stuck. Inspection revealed that this VAV was not mounted (along with three other units at this site). After the repair, additional testing verified the VAV was providing almost 20 times the air flow.

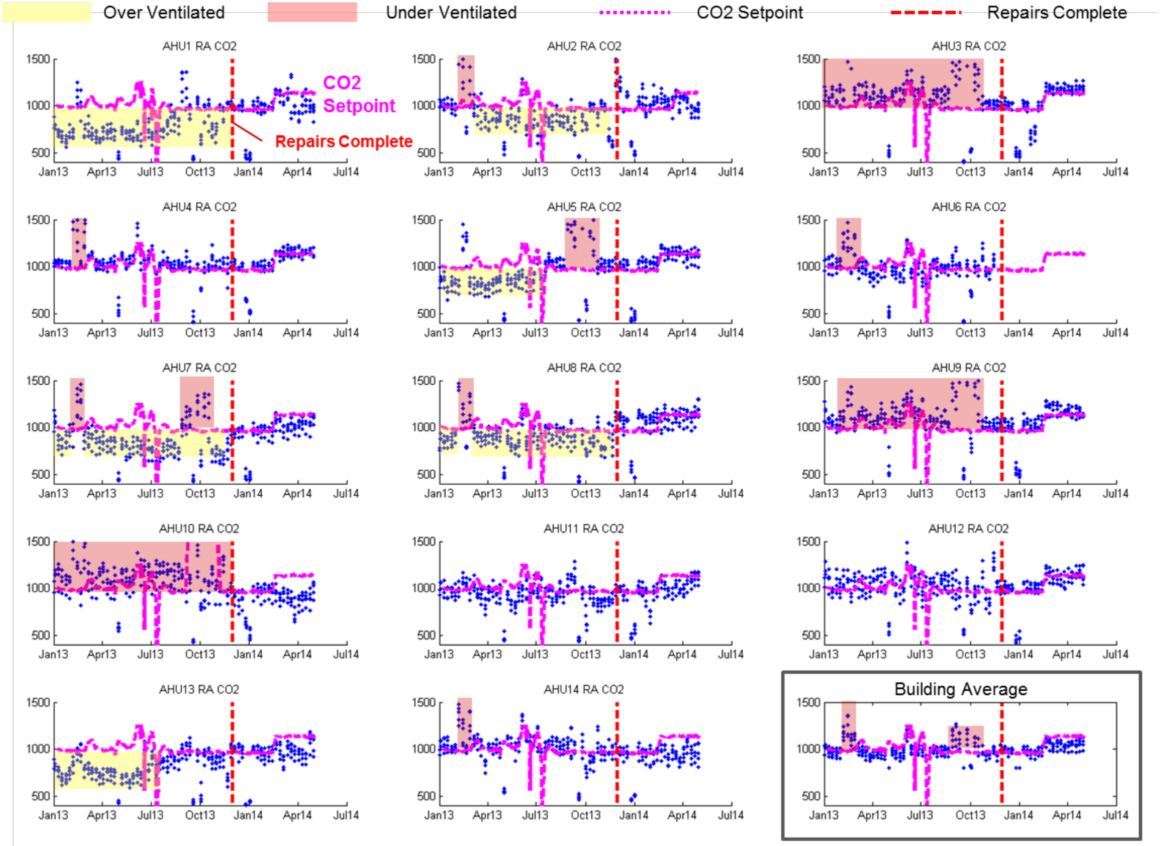

Figure 6 Resulting indoor air quality benefit. Identifying and fixing VAV faults addressed over and under ventilation of building zones, allowing effective control of CO_2 levels.

Energy savings: Since the ACT was used during the initial commissioning of Site A, no prior energy consumption baseline data was available to estimate resulting energy savings. The goal of the retro-commissioning (supported by the ACT) of Site C was to address poor cooling performance. The building's HVAC system was run 24 hours a day as the operator was not confident that the system would achieve pull-down from a daily unoccupied setback. Even with this operating strategy, the building's comfort was not always satisfied. After addressing the identified faulty terminal units (as discussed in the subsection above), Site C was able to implement an unoccupied setback mode at night and the building comfort is satisfied.

Indoor air quality: Beyond the energy benefits of addressing VAV faults, the overall indoor air quality may be enhanced due to providing the required airflow and proper ventilation as designed. Figure 6 shows representative weekday afternoon return air CO_2 levels for all 14 AHUs in Site B in relation to the desired maximum CO_2 level set-point (950 ppm prior to February). Due to the large number of VAV damper faults (as well as identified AHU faults), the HVAC system had limited control authority over CO_2 levels. This resulted in many portions of the building that were over ventilated (too much fresh air, resulting in excessive energy consumption) or under ventilated, resulting in diminished indoor air quality. After these faults had been addressed, CO_2 control was achieved.

CONCLUSION

Identifying and fixing HVAC faults can have a significant impact on energy savings, occupant comfort, occupant productivity and environmental footprint. The core challenge, however, is doing so in a scalable and cost-effective manner and ensuring that the presented results compel decision makers to take action. This paper has presented a tool and process to identify mechanical faults in VAV terminal units. This tool has been demonstrated on a range of buildings: both new and existing construction; high and low rise; North American and international. The tool substantially reduced the time to inspect the units from a typical days-to-weeks scenario to a matter of hours. The results show that VAV faults can be prevalent with an average 13% of terminal units being non-functional. Addressing these faults improved energy consumption and indoor-air quality. Finally, addressing terminal unit (and other HVAC faults) is a critical first step to ensuring other energy savings strategies (such as night-time set-back, demand-ventilation and optimal control) can perform as intended and deliver additional benefits.

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NOMENCLATURE

ACT = automated commissioning tool
HVAC = heating ventilation and air conditioning
AHU = air handling unit
VAV = variable air volume unit
FCU = fan coil unit
LBNL = Lawrence Berkeley National Laboratory
Cx = commissioning
FDD = fault detection and diagnostics
LEED = Leadership in Energy and Environmental Design
DOE = Department of Energy
α = parameter of VAV damper model corresponds to resistance ($\alpha > 0$)
β = parameter of VAV damper model corresponds to leakage ($0 \leq \beta \leq 1$)
ϕ = parameter of VAV damper model corresponds to angular offset ($-\pi 2 < \phi \leq \pi 2$)

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