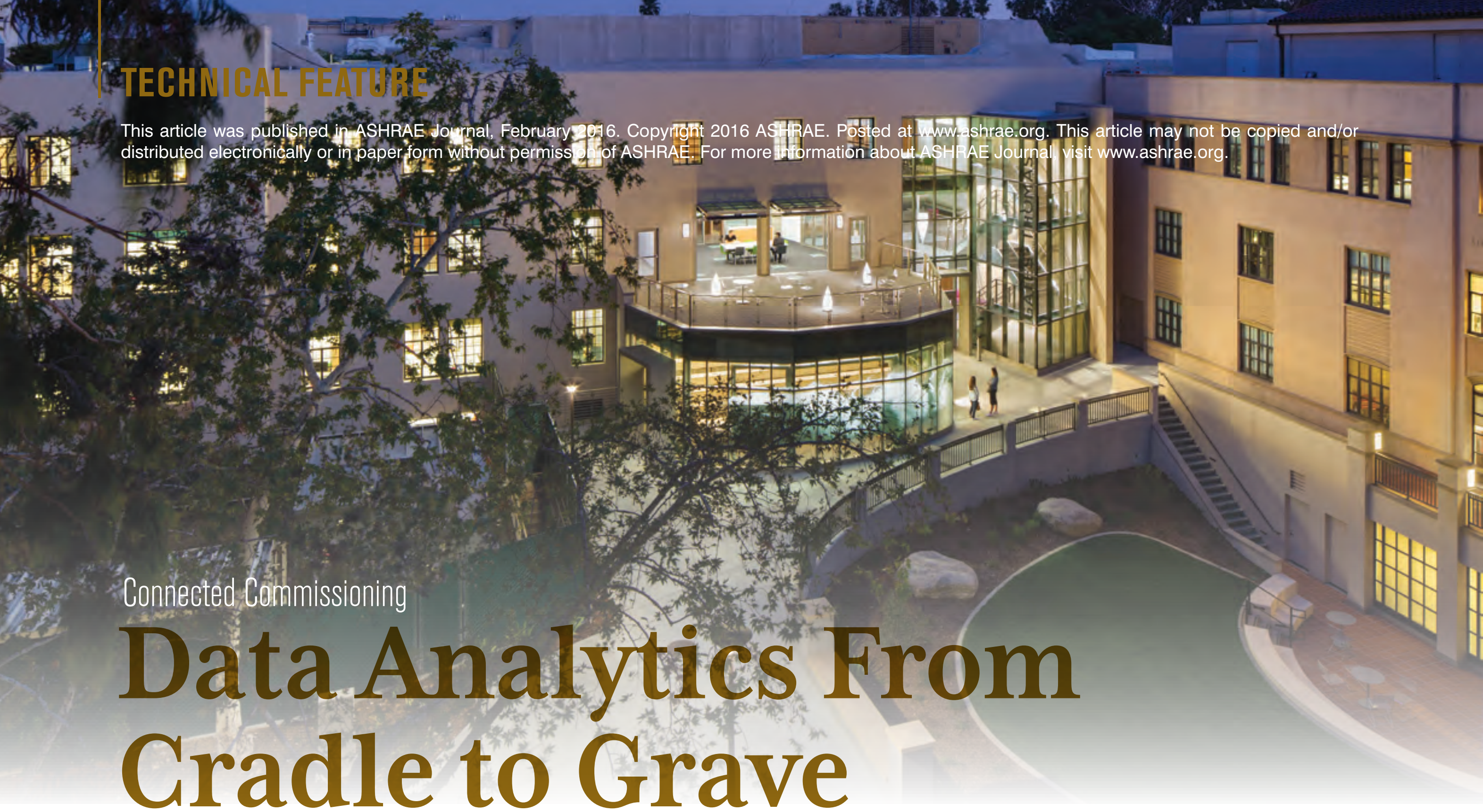

TECHNICAL FEATURE

Connected Commissioning

Data Analytics From Cradle to Grave

BY ADAM ROHLOFF; JIM MEACHAM, P.E., MEMBER ASHRAE

The last few years have seen a rapid acceleration in the integration of analytics software into building energy management and other building systems. "Building analytics," "energy dashboards" and "smart buildings" have become popular industry catchphrases, but the practical utility of the underlying applications has yet to be fully explored.

This article describes a specific application of building data analytics, referred to as connected building commissioning, that is significantly enhancing the construction-phase commissioning process and showing improved outcomes for the building owner and occupants. Onsite walk-throughs, systems checklists, and equipment-by-equipment testing are being augmented with high-resolution, real-time data monitoring, automated performance testing, and fault detection analytics that programmatically test and characterize equipment and systems failures.

These new processes have allowed for rapid, thorough, and repeatable testing of building systems and for more transparent and reliable testing results. Discussed here is the integration of these new processes into the existing new construction commissioning framework with California Institute of Technology.

Industry Trends and Growing Client Expectations

The recognition of third-party commissioning as a critical part of new construction has grown quickly in the past two decades, in large part due to the development of industry standards (e.g., ASHRAE Standard 202-2013, 2012 IECC). It has been included within voluntary green building certification programs (e.g., LEED BD&C) and more recently adopted into building codes (e.g., California Title 24, *Building Energy Efficiency Standards for Residential and Non-Residential Buildings*). Today, commissioning is a requirement for all new buildings in California and many other states.[1]

Sophisticated organizations have fully integrated commissioning best practices into their standard design and construction programs. These owners understand the different process nuances and rely heavily upon commissioning to ensure successful project completion. In turn, their expectations of the commissioning team have increased. Forward-thinking building commissioning firms recognize how building analytics and performance testing automation can serve them in this heightened role.

The California Institute of Technology (Caltech) is at the leading edge of using an analytics-driven approach

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(Left) Post renovation view of the Charles C. Gates and Franklin Thomas Laboratory on the campus of California Institute of Technology (Caltech) in Pasadena, Calif., that houses the Department of Mechanical and Civil Engineering. The Thomas Laboratory building renovation is one of several construction projects on campus that has engaged in the Connected Building Commissioning (i.e., Smart Commissioning) approach.

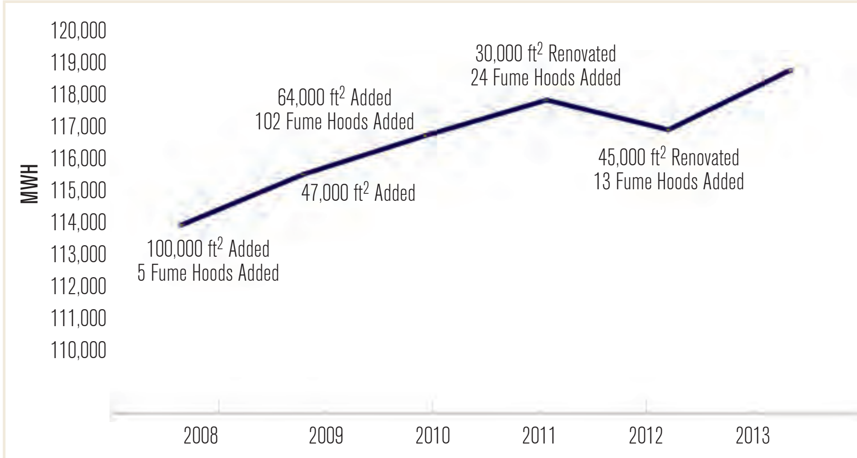

FIGURE 1 Projects driving up Caltech campus energy use. Due to the large amount of laboratory buildings on campus, Caltech has an energy intensity quotient (MBtu/ft^2) that is more than one-third greater than the average University of California campus. Its energy consumption is just under 120 GWh of electricity annually, and it pays an annual utility bill of more than $15 million. To keep energy costs and its carbon footprint in check, Caltech is always innovating on every aspect of how it delivers energy services and building maintenance.

to commissioning to achieve its high-performance facilities goals. Caltech, Taylor Engineering and Altura Associates have partnered on major laboratory renovation projects at the Caltech campus to develop a set of enhanced performance verification processes with analytics at the core. The integration of these new processes into building commissioning is referred to as connected building commissioning (CBCx) or, sometimes, smart commissioning.

The deployment of CBCx during the construction phase is delivering major payoffs at Caltech, including: improved issue resolution, greater confidence in testing acceptance, heightened accountability of the construction team, and shortened project schedules during construction. Post-construction, it is empowering the facility engineering team with unparalleled feedback on building system performance throughout the warranty-phase of a project and beyond. In this way, a critical bridge between one-time new construction commissioning and ongoing commissioning is being established.

Case Study

Caltech was initially interested in using analytics software to support the monitoring and verification requirements of its revolving fund for energy-efficiency projects. Their goal was to expose the vast amounts of building trend data that was being collected but that was not easily accessible or digestible. However, it very quickly became apparent that their initial deployment of analytics software could do much more than simply validate post-project energy savings at a macro-level. The analytics could support, in real-time, the verification of correct installation, programming and operation of equipment and systems. Furthermore, the project team saw that the same tool deployed during commissioning could continue to monitor building performance during occupancy with the same level of scrutiny, helping to avoid building drift and the cycle of recommissioning that often becomes necessary.

This concept of ongoing commissioning as an alternative to discrete commissioning cycles is not new, but until recently, it has been rarely achieved due to the difficulty of deploying and maintaining a real-time building monitoring and performance analysis tool.

The Caltech laboratory major renovation projects described in this article are high energy intensity buildings due to critical-level equipment that requires constant and precise amounts of ventilation. In this way, these buildings are ideal case studies that help to fully illustrate the differences and benefits of connected commissioning as compared to a traditional commissioning approach. The same concepts can be applied to other critical facilities: hospitals, chemical processing plants, data centers, manufacturing floors, etc., as well as any buildings where central automation systems are heavily used.

Commissioning Standards and Where CBCx Fits In

CBCx is a new enhancement to the established commissioning framework that has been developed over the past three decades. ASHRAE Standard 202-2013 defines building commissioning as:

"A quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that all of the commissioned systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the owner's project requirements."[2]

Other organizations such as the ICC, Building Commissioning Association, and the California Commissioning Collaborative offer variations of this definition, but all convey that the purpose is to ensure that operational performance meets owner expectations.[3] The commissioning authority (CxA) is the entity tasked with leading the commissioning process and managing the commissioning team. Commissioning is intended to start at project conception, and continue into design, throughout construction and into the post-occupancy warranty period. The Connected Building Commissioning approach (CBCx) described in this article builds upon the traditional definitions of commissioning to offer new levels of performance testing and deeper connections between construction and operations.

So Why Is It Worth Trying To Improve?

Performance Testing, also known as Functional Testing or Functional Performance Testing, is intended to verify that equipment, assemblies and systems meet defined operational performance criteria. While only a part of the overall commissioning process, the design and construction team relies heavily on Performance Testing as the final validation that all equipment and systems meet owner expectations and the building is ready for occupancy. Data shows that approximately two-thirds of the entire commissioning budget is spent here, and another 15% to 20% is spent on construction observation, which directly precedes the testing period.[4] CBCx specifically targets both the prefunctional and functional testing period, where the greatest opportunities for improvement and largest payoffs in terms of budget, time, and added quality assurance reside.

What Does Prefunctional and Acceptance Testing Involve and How Does CBCx Support It?

The CBCx process evolves the traditional prefunctional checklist process to identify deficiencies earlier and to better integrate the controls programming and equipment start-up processes. This new prefunctional process begins in the design phase with the inclusion of detailed acceptance criteria in the project

Commissioning Approaches

Traditional	CBCx
OPR/OBD	OPR/OBD
Cx Specifications	Cx Specifications
Design Review	Design Review
Submittal Review	Sequence of Operations Development
Prefunctional Checklists	Submittal Review
Functional Performance Tests	Detailed Acceptance Tests (wPFCs)
Systems Manual	Automated Functional Tests
Seasonal Performance Tests	Test Validation with FDD
Warranty Review	Controls Optimization
Future Recommissioning	Systems Manual
	Continuous Warranty Review
	Ongoing Commissioning

FIGURE 2 The traditional design and construction workflow requires some adjustment to make the most of the insight available through the connected building approach to commissioning. More upfront information about automation controls' sequence of operations can serve to avoid schedule delays and added costs later, compressing the whole cycle.

specifications. During construction, the focus is on achievement of the acceptance criteria, not just the completion of traditional checklists. The most effective way to minimize performance testing hours and maximize the value of the test results is to ensure that equipment and systems are fully ready for testing. This may seem obvious; however, it is not uncommon to functionally test equipment/systems only to find they were not properly installed and/or started up, or that the controls programming had major flaws or deviations from the sequence of operations (SOO). The result is often additional rounds of testing, wasting time and money for the entire team.

The traditional prefunctional checklist phase uses multiple tools to reduce the likelihood of these occurrences, including:

- Review of subcontractor completed equipment start-up forms;
- Development of prefunctional (i.e., construction) checklists by the CxA, customized to the equipment, and consequent completion of these checklists by installing-contractor and review from CxA;
- Onsite walk-throughs and regular construction observation by CxA to ensure proper installation;
- Control system observation, trend review and review of contractor pre-tests where applicable; and
- Generation of issues log by CxA and distribution to contractor for resolution during above steps.

While these processes and checks along the way can help to reduce performance testing time, they do not guarantee system readiness. The prefunctional processes themselves can become quite lengthy and require extensive documentation exchange between contractors and CxA. In practice, the pace of construction may not allow sufficient time for satisfactory documentation completion, review and resubmittal. Moreover, the trade contractor's interpretation of "complete" or "test-ready" can vary from the commissioning engineer's understanding. While walk-throughs are helpful, the CxA cannot gain the same level of visibility into the installation of equipment from a day or two of observation as the contractor obtains from daily involvement.

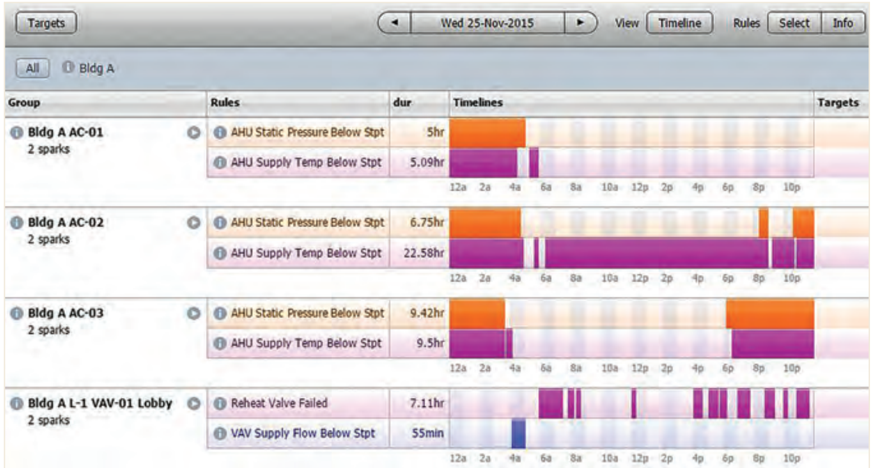

FIGURE 3 Custom fault detection rules shown above quickly highlight equipment failures across an entire building. All equipment and/or zones that have failed can be quickly identified in this manner. Equipment performance can be further investigated by clicking into the individual equipment pages and observing relevant data trends (*Figure 5*). These dynamic, web-based reports can then be shared with other project members and used to expedite and eventually verify issue resolution.

On the automation controls side of commissioning, trend review can be a powerful tool, but also a large time-sink that only provides a limited view of the system. The availability of data trends also depends on the level of sophistication of the controls software historian and the controls contractor who deploys it. Often, trend deployment is an afterthought for the contractor and in the design of the controls software itself.

CBCx tools offer a greatly enhanced prefunctional test period. The alternative to the documentation-heavy approach of traditional prefunctional testing is to integrate analytics software to all equipment that is being controlled by the building's central automation system (or other networked systems when possible, e.g., lighting, fire and life safety). In this way, every setpoint, sensor and command point for all equipment can be trended, monitored, and analyzed as a system. Having this data available upfront, immediately after equipment startup, allows the commissioning engineer to validate whether systems are online, and at least nominally operational. Equipment with glaring operational failures can immediately be detected and reported to the contractor before beginning functional testing. Some common issues that prefunctional data monitoring and intervention can resolve are:

- Faulty actuators, valves, and dampers that do not stroke fully open and/or closed;
- Sensors that are not calibrated or are not communicating at all;
- Incomplete point-to-point checkouts; and
- Fans, pumps, compressors, and other mechanical equipment that are in fault or alarm.

These data trends can easily be shared through web-based interfaces or emailed reports, so any member of the construction team can see what failed, when it failed, and for how long it remained in failure mode. This enhanced level of information leads to a quicker understanding of the root cause of failure, and the consequent resolution of the issue. Once an issue is resolved, the same tool that identified failure can verify successful operation.

Furthermore, by including detailed acceptance criteria in the enhanced prefunctional testing process, the CxA can begin performance testing with greater confidence that the focus can be on system-wide performance, as opposed to failures due to incomplete work or insufficient programming. CBCx also provides a better understanding of how all the equipment and systems in the building are interoperating. In general, the CxA has more data and better decision-support as he tackles the more complex dynamics of a modern commercial building.

What Is "Performance Testing" and How Does CBCx Improve It?

In most cases the sequence of operations (SOO) serves as the primary reference upon which equipment/system performance is measured, along with other supporting construction and design documentation. The performance testing methods, required test conditions and criteria for acceptance are developed from these documents and are commonly referred to as the test procedures.

Test procedures can include both passive and active testing methods. Under passive testing, equipment is allowed to operate under natural, automatic conditions while being recorded for a period of time determined to be sufficient to evaluate acceptance. By necessity, these are often longer term test periods (days to weeks), as it is unpredictable when natural conditions will coincide with required test conditions. Active testing forces equipment into the test conditions to then observe and record equipment response. Test execution details are documented on written or electronic forms while a data logger or automation system records time-series trend-data for specific data points. These trends are then post-analyzed and performance is compared to the expected response to determine acceptance.

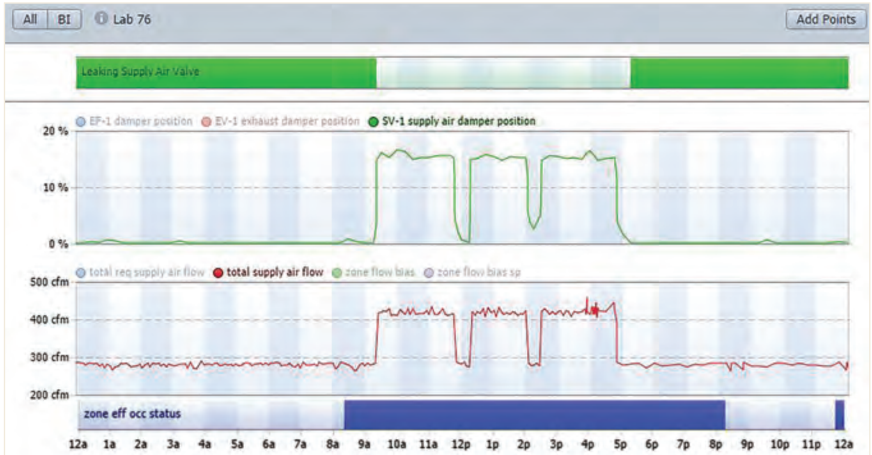

FIGURE 4 In this example, the "Leaking Supply Air Valve" fault detection rule is being triggered and shown at the top of the chart as a green bar trend. The FDD trend is time-aligned with other relevant trend data from this laboratory supply air valve controller. This view allows for quick verification that the supply air valve is being commanded fully closed (at 0%) but flow is still being detected from the airflow monitoring station, an issue commonly encountered during building commissioning.

The forced conditions can be achieved through the use of automation system overrides by the controls programmer (equipment schedule adjustment, speed/position commands, temperature/pressure sensor overrides) or field interventions (occupant thermostat resets, in-hand valve/window/sash position adjustments, etc.). Active testing is generally required to comprehensively test the SOO in a timely manner.

Increasingly complicated systems (e.g., chiller plants, fume hood labs) combined with more stringent energy-efficiency goals will necessitate a more detailed SOO, which, in turn, requires greater sophistication and customization of the testing procedures. These tests will often require a lengthy series of forced conditions at specific ordered time durations to sufficiently determine acceptance. Thorough, well-designed test procedures can verify that even the most complicated SOO has been correctly programmed; however, the time and resources spent on these tests can be enormous, particularly when dealing with large numbers of equipment or complicated systems.

In the effort to mitigate time spent, it has become common industry practice to use a sampling approach to testing where possible. On large projects, sampling is used during submittal review, construction observation, checklist review, and performance testing, where only a fraction of the total number of similar type equipment, drawings, events, etc. are directly evaluated. Sampling techniques include random statistical sampling and less formal professional judgment methods.[5] These techniques are often necessary on large-scale projects with limited budgets, but they must be balanced with quality assurance steps to deliver the level of confidence in the commissioning process intended by the project team.

Automation in Performance Testing Execution is a Game Changer

With CBCx, the step-by-step test procedures for each piece of equipment are still included. However, the execution of these tests is transformed from a manually executed, time-intensive process to an automated process that can run a virtually limitless sequence of override steps on multiple equipment at once, without the need for human intervention. This process unlocks an unparalleled degree of scalability, repeatability, and schedule flexibility in the testing regime that is impossible with a traditional approach. Specifically, automated testing features the following differentiators:

Testing of 100% of equipment is viable in a wide range of conditions, eliminating the risks associated with sampling. For example, an automated script that is written to test flow setpoint reset control of a variable air volume (VAV) box can be run on a single piece of equipment, or on 100 VAV boxes of the same type, with virtually the same level of effort. With large numbers of similar equipment, automation will save time while providing a higher degree of quality assurance.

Where a sampling approach is not traditionally used, such as with laboratory fume hoods and in other critical environments, the time savings of automation is even more significant. Using automation to replace repetitive testing also greatly reduces fatigue and general human error, a factor that should not be considered trivial on critical large-scale projects.

Automated test procedure scripts can be scheduled to execute at any time, including overnight, when occupants and contractors are out of the building. This is a major convenience, as performance testing generally occurs at the end of the construction period when various contractors are scrambling to complete work on time. Additionally, if construction is behind schedule, occupants may already be starting to occupy the building. In any of these cases, testing can be scheduled to work around contractor, occupant or facility schedules.

Retesting is no longer limited by budgetary constraints. Test procedure scripts, once written, can be run as many times as needed with minimal additional effort. The commissioning authority can confidently set the expectation that 100% of equipment will pass functional testing. At Caltech, this capability was invaluable. Certain labs contained multiple fume hoods, and movable curtain walls that created subzones requiring multiple supply and exhaust valves. These systems all had to be controlled in concert to meet zone comfort needs and ventilation requirements; of course, all while operating in the most energy-efficient manner possible. Many of these laboratory zones needed to be retested up to five or six times as the controls were being optimized with each retest. Achieving this level of performance would have been extremely difficult without the power that automated testing and analytics provided. While that may seem the rare exception, the reality is nearly every building or renovation will hold unique characteristics that require special attention, and most likely multiple rounds of retesting.

Test Validation Using Fault Detection and Diagnostics

The examples above highlight the unprecedented increase in speed, flexibility and comprehensiveness that automation can offer during test procedure execution. The other component of performance testing is test validation; that is, the verification that equipment performs as expected during test execution. At Caltech, this task was also supported by the same building analytics platform that executed the tests, using advanced fault detection and diagnostics (FDD).

In traditional testing, the CxA would manually verify expected equipment response hand-in-hand with test execution, one piece of equipment at a time, with the in-person support of the controls contractor. Not only is the approach labor intensive, but with sophisticated sequences of operation, it can be nearly impossible to check, in real-time, all the expected responses that should occur for a given override. An accepted solution to these challenges is to rely on trend review after testing is done to validate responses.

Again, in a traditional approach, one-at-a-time trend validations that rely on building automation system trends can be extremely tedious and are limited by the capabilities and time of the controls contractor and their controls engine. Using FDD, fault rules are written that analyze the equipment trend data for any unexpected responses (or expected responses) during known times when a test is under execution. Some basic FDD rules might include:

- Air handler enabled during unoccupied hours;
- Air handler supply air static pressure setpoint above/below setpoint;
- Air handler static pressure setpoint reset fails to reset;
- Air handler economizer damper stuck open/closed;
- Zone space temperature above/below setpoint;
- VAV supply airflow below setpoint while supply damper full open; and
- Boiler enabled while no heating demand exists.

The rules listed above represent a generic outline of the scope of FDD; however, rules can be written to validate specific items of a sequence of operations as well as be tuned to only trigger based on minimum time and or error thresholds. Using these rules, equipment failure or acceptance can be highlighted automatically, with the start time and duration of each failure made clear and timestamp-aligned with the rest of the supporting trend data as shown in *Figure 4*. This allows the CxA to quickly prioritize failed equipment and drill into the data only when it matters, to find root causes as shown in *Figure 5*. These issues can then be reported to the project team much faster. Sharing this data through web-enabled HTML interfaces allows other members of the project team (e.g., the design engineer) to easily validate the commissioning authority's findings and find their own insights. Exposing the performance of the controls system directly to the engineer in a meaningful and digestible way creates opportunities for iterative improvements to both design and execution that are normally disconnected.

The FDD techniques used at Caltech have proven enormously powerful. In fact, the same fault rules that run during performance testing are now used during normal operation on a continuous basis. The programming behind these rules allows ultimate flexibility in tuning of duration, threshold of acceptance, and interdependency of other equipment in the building system. The CxA is able to cater the FDD rules to individual needs. During commissioning, these needs are tailored toward performance testing validation. Post commissioning, these same rules and trends can be tuned for operational purposes. As a result, the combination of a robust analytics platform and CBCx-style design and construction processes become the foundation of and gateway to long-term energy management and operational excellence.

Practical Considerations

Successfully deploying performance testing automation during commissioning requires several considerations, both from a technical and project/building management standpoint. The basic considerations include:

- Selecting an appropriate analytics platform and personnel who can support its deployment and maintenance. Technical support can be internal or external, depending on the resources of the organization.

- Selecting a commissioning authority who is familiar with the approach or willing to work with and/or develop these capabilities with the organization or other external team members.
- Incorporating the expectations and requirements of automated functional testing into bid specifications. This relates most directly to the commissioning and building controls specifications.
- Training facilities staff in how to use the analytics platform following construction. Automated performance testing during commissioning is simply one use case of building analytics platform. If deployed strategically, the same analytics platform can be used throughout the building life cycle, including but not limited to: energy management, ongoing maintenance, tenant billing, and retro-commissioning and/or ongoing commissioning.

Integrating Analytics Into the Building Automation System

There are a dozen or more building operational analytics software suites on the market, and the right solution for any particular building is dependent on the building type, scale and team that will be using it. When choosing the right platform for use, some important considerations are:

- What are the integration capabilities of the software? Can it connect to the specific automation systems that we have? What data communication protocols does it rely on? Can these protocols support my data needs?
- How many data points do I need? How much of the automation system do we need to integrate? Do we require real-time data or can we rely on syncing trends from the automation system?
- Who will integrate and manage the database? In-house staff? Third-party installers? The software developer themselves?
- What level of interaction do you desire? Fully managed solution? Customization that can be done in-house/out-of-house? What kind of in-house programming/analytic engineering capabilities do you have?
- How will this tool fit into your current design and new construction work processes? How will this fit into

your current operations and maintenance work processes?

- What kind of FDD capabilities does the software have? How does that compare to what you expect from the software? Are "out-of-box" analytics sufficient or do you require customization?

Tailoring Bid Specifications for Analytics and Automated Performance Testing

Standard bid specifications for building controls do not prohibit the use of analytics and automated performance testing; however, including certain language into the specification and actively communicating these expectations upfront can greatly improve what your analytics platform will be able to achieve.

When it comes to the building controls industry, the diversity of equipment manufacturers, data communication protocols, network architectures, controls system software, and the proprietary programming behind these products remains a challenge when integrating data into a single platform on a large scale.

Analytics integration can be eased greatly by enforcing standard industry protocols (e.g., BACnet) and powerful open-source tagging and data modeling conventions (e.g., Project Haystack). Organizations should carefully select vendors that use and promote open industry protocols so valuable data does not become locked behind a single proprietary technology. Internally, enforcing a common naming taxonomy makes it far more realistic to integrate thousands of automation system points into an historical trend database efficiently. Any serious analytics effort should begin with developing this in-house point taxonomy and vendor specification that can be standardized across your portfolio.

Better Integration Decisions Leads to Smarter Buildings

CBCx, and the Internet-of-things mindset that has made this approach possible, have opened a new landscape in building design and construction. Sophisticated operating sequences are no longer limited by the ability to enforce their performance at the time of deployment and can be validated continuously during operation. The bridge between construction and operations is supported through a singular analytics platform that is flexible enough to meet the needs of all players at all points in the process. To ensure success, the software requirements need to be considered early and repeatedly throughout the design/construction cycle by a multi-disciplinary project team. Forward-thinking commissioning firms can help steer the team in defining a software data platform that serves project construction needs *and* extends into the normal operations phases of the building's life. Done correctly, it will put the most useful and valuable information at the fingertips of the building managers and operators and empower occupants and the facilities staff to get the most out of their building.

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