

FAULT DETECTION AND DIAGNOSTICS

Enabling techno-commissioning to ease building operation and improve performance



Issue Brief

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INTRODUCTION

The facility manager of tomorrow will manage his or her building continuously, strategically improving occupant comfort and energy management through automated, connected technologies. Unlike today, where managers generally respond reactively to building systems alarms and occupant comfort complaints, techno-commissioning proactively uses fault detection and diagnostics (FDD), or predictive maintenance, to identify issues that will result in wasted energy or premature system failure and its attendant repair and placement costs.

Automated systems can detect anomalies in performance, analyze buildings systems, diagnose the problem, alert and make recommendations to the facility manager, and in some cases even automatically generate work orders or take corrective actions directly within the building management system. Such systems make buildings much easier to operate efficiently and with maximum occupant comfort, and also make buildings more economically competitive. Today, well-managed buildings are usually, at best, using a clear preventive maintenance schedule combined with periodic building retro-commissioning. A techno-commissioning approach can improve the persistence of retro-commissioning benefits and establish a framework for ongoing commissioning.

A traditional building automation system (BAS) provides alarms that identify problems in a building after they have happened, based on system thresholds. For example, a room temperature alarm activates if the room rises above or falls below the high or low temperature setpoints. The response thus happens after the fact, when the temperature is already too high or too low. The BAS alarm requires further analysis by the facility manager to identify the fault and the way to fix the problem. In addition, BAS alarms primarily focus on critical failures or problems that will lead to significant comfort or repair issues.

In comparison, techno-commissioning with an FDD system focuses on identifying non-critical deficiencies in which the building environment still performs but is not optimized to minimize energy or maintenance expense. The FDD system can recognize when a condition is starting to deviate from the correct values, or when a system is operating sub-optimally, so that the facility manager can see the problem before it actually occurs. It can detect not only a trend in an adverse direction, but also the cause of the trend, so that the facility manager can fix the problem quickly. For example, FDD for room temperature has no high and low thresholds. The system looks at trends over time and detects any adverse temperature trends, along with the causes of those trends, be it setpoints, occupancy, or aspects of how a variable-air-volume (VAV) box is performing. The fault data lets the facility manager see the problem before the temperature actually rises above or sinks below acceptable levels.

Modern cars and airplanes already use computer analytics to find and diagnose faults and thereby avoid future system failures. In a modern car, instead of changing your oil at 3,000 miles, measurements from sensors detect and can tell you that the motor oil has a certain level of contaminants and now needs to be changed. The same is now true for buildings: FDD can use measurements to determine when equipment and systems need servicing based on their actual condition.

FDD can make buildings much easier to operate and maintain on a daily basis. The following two sections outline how FDD can help improve both building operations and the long-term building management strategy, and so help reduce the long-term cost of operating a building.

EASIER DAY-TO-DAY BUILDING OPERATIONS

In a building using FDD, the facility manager or a building technician is notified of a system problem when it occurs. In some cases, he or she may be able to review the information and act remotely, or send someone with the right parts to make a repair, if needed.

FDD software not only detects faults; it can instantly provide information based on analytics (e.g., energy or cost impacts of the fault) to help the building operator screen and prioritize which faults to fix based on safety, operational implications, code compliance, cost, impact on occupant comfort, and other factors. Without techno-commissioning, a facility manager's maintenance strategy is strictly schedule-based and is not related to the actual operating conditions of the building and its equipment. With FDD, the analytics tell the manager what needs to be done today based on current system condition and performance, as well as what items can be deferred.

FDD and lifecycle asset management software tools can help executives calculate and compare the costs and benefits of fixing a problem versus waiting to fix it later. Component and system failures have varying impacts on energy consumption and comfort – FDD can analyze the energy penalty and cost of equipment failure and can anticipate the impact of a failure on other equipment functions. Assignment of dollar values to faults can help a facility manager plan for maintenance and commissioning program budgets.

Definition of a fault and problems that can be detected with FDD

A fault is a deviation in the value of at least one characteristic variable from its normal expected behavior.

Faults that can be detected through FDD include:

- HVAC systems that improperly simultaneously heat and cool
- Excessive outdoor air intake and conditioning
- Under-utilized free cooling potential
- Equipment malfunction (such as broken/leaking valves, broken/stuck dampers, sensors out of calibration)
- Systems with the wrong setpoints and operating schedules
- Unintentional manual overrides
- Lack of energy-saving control sequences (such as chilled water reset)
- A bad bearing in a motor or compressor (the bearing then can be replaced before the whole gear box fails and becomes an emergency repair)
- Misaligned motor, rotor imbalance, or cracked rotor bar
- Dirty filters or strainers
- Incorrect refrigerant or oil levels
- Pumps with throttled discharges
- Short cycling of equipment
- Excessive oscillation (hunting) of control points and/or control loop tuning needs
- Incorrect fan and pump speeds, pressures, or low flow rates.
- Improper building or space pressurizations (negative or positive)
- Inefficient boiler combustion
- Excessive building peak electrical demand

IMPROVED LONG-TERM MANAGEMENT STRATEGY

Today, FDD can achieve many of the benefits of retro-commissioning on a continuous basis and can increase the persistence of performance improvements. FDD does have some advantages over traditional retro-commissioning. These will become even more pronounced as the up-front cost of FDD technology integration falls and as buildings become more digitized with open protocol communications:

- FDD can enable continuous retro-commissioning by ensuring that a building is meeting the current facility requirements on an ongoing basis. FDD cannot be equated with retro-commissioning, since it does not by definition correct the faults detected and diagnosed. However, it does enable retro-commissioning activities to become part of routine building operation and maintenance, instead of a periodic event.
- FDD requires less time from highly trained building engineers to implement, making it quicker and more cost-effective to do on an ongoing basis.
- FDD can be used to help identify the cost-optimal timing for retrofit measures and facility upgrades.

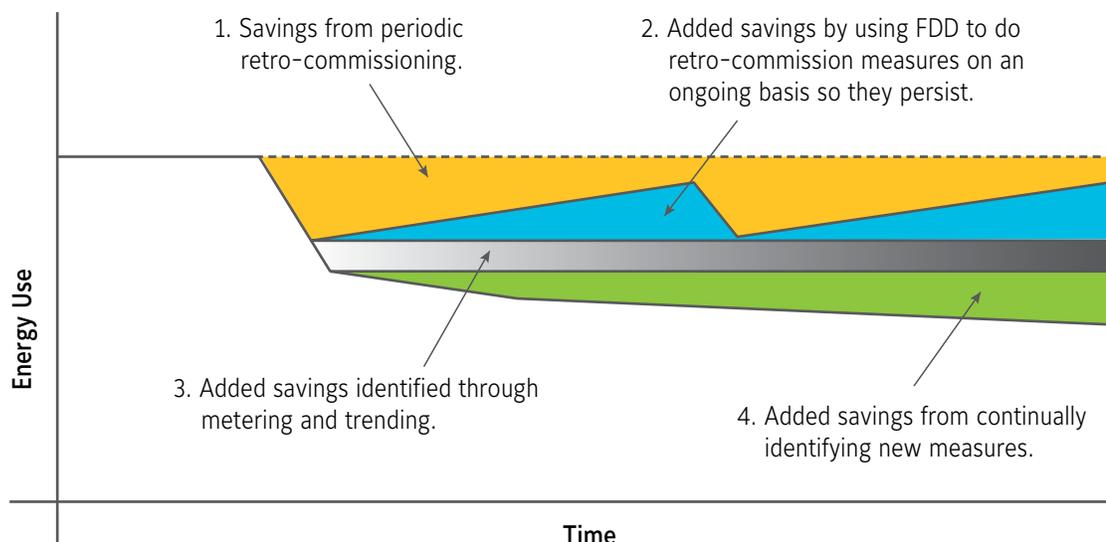
ENERGY SAVINGS

Because it works continuously, there are three ways in which FDD can enable additional energy savings over traditional retro-commissioning.¹

1. Improved persistence of efficient operations: Over time, energy efficiency will degrade due to changes in equipment performance and operation issues, such as temporary changes to schedules that become permanent and setpoint changes requested by occupants. FDD can automatically detect deleterious energy efficiency changes in near real time. Similarly, the building's use and operating requirements often change, resulting in a new optimized state.
2. Performance tracking: energy savings investments and practices can be monitored and verified, and even used to detect when performance degrades.
3. New improvement measures and upgrade opportunities can be identified on a continuous basis.

¹ "Monitoring-Based Commissioning: Benchmarking Analysis of 24 UC/CSU/IOU Projects." Evan Mills, Paul Mathew. LBNL. 2009.

Figure 1. Additional Energy Savings Beyond Retro-commissioning



FDD METHODS

Various FDD methods have been developed, but the leading methods are rules-based, performance indexing, and statistics-based FDD. The three complement each other well. For more technical descriptions of these methods using another classification scheme, see a paper by PNNL.² The following figure compares the level of sophistication of the various methods, and how a combination of the methods provides better FDD.

Figure 2. FDD Levels of Sophistication



FDD Method 1: Rules-Based

Rules-based FDD establishes specific expected conditions for building systems and clear limits or ranges of performance.³ Rules are essentially very advanced BAS alarms. But, unlike BAS alarms that focus on identifying critical problems in the building, FDD rules focused also on identifying non-critical deficiencies in which the building environment still performs, but is not optimized to minimize energy or maintenance expense. For example, a rule might say that the facility manager should be notified if the heating setpoint temperature for a room is raised above 72°F degrees. Rules can also then be set to track trends in the subsystems that affect that temperature, so that the cause of that temperature rise can be easily identified. Rules may also analyze how multiple systems interact with each other. For example, a rule might say that if both condition x and condition y occur at the same time, then a fault should be reported.

The advantages of rules-based FDD is that it is good at capturing both fundamental principles of building operation and the logic and experience of building experts, and then comparing performance against those expected rules. Rules are also straightforward to implement, making them relatively low cost. Also, rules can be easily tailored to address the needs of a specific building or a custom-built piece of equipment.

The limitations of rules-based FDD are:

- Rules often can't adapt over time on their own as building usage changes; a building engineer needs to update the rules as changes are made in the building.
- Rules can grow unwieldy and hard to scale because so many rules are needed to effectively catch all possible faults.
- Events or faults must occur before a rule notifies the facility manager of a problem, so they limit how proactively a facility manager can be.
- Poorly conceived rules can generate tremendous numbers of false alarms. There is a tradeoff between rule sensitivity and the probability of generating false alarms.

Many of these limitations can be overcome and complemented with performance indexing and statistics-based FDD, as explained in the following sections.

² "Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems—A Review, Part I" Srinivas Katipamula and Michael R. Brambley. HVAC&R Research. January 2005.

³ "Application of an Automated Fault Detection and Diagnostics Tool Identified Faults in HVAC System Operation and Potential for Associated Energy Savings Denver Athletic Club, Denver, Colorado" Mike Eardley, University of Colorado. 2006.

"Results from Field Testing of Air Handling Unit and Variable Air Volume Box Fault Detection Tools." Jeffrey Schein, Steven T. Bushby, Natascha S. Castro, U.S. Dept. Of Commerce. John M. House, Iowa Energy Center. 2003.

FDD Method 2: Performance Indexing

Performance indexing is a diagnostics information management system – it simplifies and presents complex building performance data in a highly usable format. Performance indexing provides an easy way for operators to discover equipment performance issues that could potentially degrade energy efficiency, occupant comfort, and equipment life. It then allows them to take timely corrective action long before a BAS alarm is generated. Performance indexing provides a relative ranking score indicating facility and equipment performance on a continuous basis (typically every 15 minutes, or as frequently as the facility manager wants).⁴

Performance indexing uses the same types of thresholds for system performance as rules-based systems and, as with rules, the thresholds are based on the fundamental principles of building operation and the logic and experience of building experts. But, in addition to indicating when a threshold has been reached (as with rules), performance indexing indicates on a continuous basis where a system lies between its ideal setpoint and the threshold for a fault, on a scale of 0-100. If a system or subsystem is between 85 and 100 on the scale, then it is in good condition, and the difference between the actual performance and the ideal setpoint is minimal. If a system is between 50 and 85 on the scale, then the actual conditions have deviated significantly from the ideal, and the facility manager should keep an eye on that system. If the system is between 0 and 50 on the scale, then action needs to be taken soon to return the system or subsystem to ideal conditions. Performance indexing therefore gives facility managers an easy way to track performance of building systems and subsystems in real time. Results for each subsystem are combined to provide a picture of system, group, and whole-facility performance levels.

This hierarchy of information about subsystems, systems, groups and whole facilities provides a holistic evaluation of performance and helps facility managers uncover the root cause of unacceptable performance. For example, root cause analysis can help a facility manager identify why a room is regularly too hot or too cold. The temperature problems could be caused by a VAV box that needs adjusting, or by an air handling unit with incorrect levels. If the performance index indicates that the VAV box is performing at 100, but the air handling unit is at 40, then the facility manager can see it is the air handling unit that needs attention. Problems can be detected efficiently by monitoring for changes in the performance indices.

FDD Method 3: Statistics-Based

Statistics-based FDD uses different types of statistical analytics to detect faults. While statistical approaches are often more complicated to set up, they are more scalable and adjustable over time. For example, statistical FDD can scale easily and can adapt on its own to seasonality and changes in the operating schedule of a building.

There are three statistical approaches to FDD: comparison to prior operation, peer group analysis and statistical modeling.

⁴ "Research Methodology for Building Automation Performance Index." Shariar Makarechi, Southern Polytechnic State University, Marietta, GA and Roozbeh Kangari, Georgia Institute of Technology.

Comparison to Prior Operation

A statistical comparison of building or equipment operation today to past operation can detect many faults. The advantage of this approach is that operational or equipment changes occurring over time can be detected with predetermined statistical confidence without human intervention. The disadvantage to this approach is that problems that have always been present may not be detected. One solution to this is to commission systems before implementing this approach. Alternately, a skilled resource is needed initially to identify the data that coincides with a good operational state.

Peer Group Analysis

Peer group analysis compares similar systems within a building to each other to look for statistical anomalies. For example, if the control errors of a statistically significant number of similar VAV boxes are compared, high outlier values would indicate that a fault is likely present. Peer group analysis is not appropriate for systems with relatively few (< 25) like types of equipment, such as chillers and boilers. Someday, it may be possible to compare single pieces of equipment in multiple similar buildings, but today, peer group analysis is usually possible only in a single building or a campus of related buildings. Also, peer group analysis only detects issues with equipment. Issues in the environment related to occupant comfort are less well covered (though issues with occupant comfort may be indirectly detected and corrected, or might be directly detected with occupant input).

Statistical Modeling

Statistical modeling creates targeted expected performance for building systems and tracks and compares that to actual performance data from the BAS. Modeling is the hardest statistical approach to set up for a building because it takes skilled people with deep building knowledge. However, once it is running, detailed analytics are possible. Statistical modeling works particularly well for large systems, such as chillers. Statistical modeling enables the degree of degradation of equipment to be monitored over time and compared to the expected rate of degradation.⁵ The disadvantage of statistical modeling is that it will not catch faults that existed before implementation of FDD.

FDD Method 4: Combined Approach to FDD

A combined approach to FDD, using rules, performance indexing and statistical approaches, provides the most complete diagnostics and enables the greatest improvement in building efficiency. The three approaches complement each other well. For example, an engineer may know that a certain rule is needed, but not know exactly how to set the thresholds for that rule. In that event, statistics might be used to set the threshold automatically. Statistics can also be used to review the appropriateness of rules over time. The facility manager's experience will be similar regardless of the approaches used for FDD, but a combined approach is likely to identify more opportunity for energy savings and improved building operations.

Case Study, Western Kentucky University

Western Kentucky University began using FDD software to analyze its BAS system data. In the first 120 days, the staff detected a range of building system faults, such as improper sequencing, improper valve and damper positions, improper ventilation, and missed opportunities to reduce peak demand. In addressing the faults, the university achieved two goals, creating more comfortable learning environments on campus and recovering its investment quickly.

⁵ "Improving Efficiency and Reliability of Building Systems Using Machine Learning and Automated Online Evaluation." Leon Wu, Gail Kaiser, David Solomon, Rebecca Winter, Albert Boulanger, Roger Anderson. Columbia University.

"Model-based fault detection and diagnosis - status and applications." Rolf Isserman, Darmstadt University of Technology. 2004.

Case Study, IBM

IBM's campus in Rochester, Minn., consists of 3.2 million square feet of space in more than 35 interconnected buildings. The initial phase of the project integrated information from 87 of the site's largest and most heavily used air handling units as well as lighting and perimeter heating in three buildings. Now, facility managers say they can solve problems as they find them, instead of searching for the needle in the haystack. An automatic work order is generated when critical systems have faults, such as a hot data center air handler. The organization estimates year-over-year incremental energy savings, even though the facilities have undergone years of continuous energy efficiency improvements.

THE FUTURE: PROGNOSTICS BASED ON BIG DATA

In the future, automated tools will not only be able to detect and diagnose faults, but prognostics will provide predictions about the future of buildings and their equipment. Prognostics could be based on a combination of maintenance data, operation statistics, parts ordering data, weather data, warranty data, location data, and other data sources, not for just one building, but many buildings, bringing big data to commercial buildings. Prognostics will be able to predict precisely the remaining useful life of building components, when mechanical breakdowns are likely to occur, the amount of energy wasted, and the other future impacts of actions taken (or not taken) today to resolve faults. It will include suggestions for how to stay ahead of the curve on maintenance and avoid faults and failures, in a way that is similar to, yet more advanced than, the way amazon.com can make purchase suggestions. Prognostics will include the ability to look at one system in the context of others and see how components are interacting: 'Based on what we know about your chiller, you likely also need to fix a certain other component in addition to the one that is broken today.'

CONCLUSION

Techno-commissioning with FDD makes buildings much easier to operate on a day-to-day basis, allowing facility managers to better meet occupant needs by anticipating problems before they arise. FDD uses three main methodologies: rules-based, performance indexing, and statistics-based. When combined, these methods create a powerful tool to help facility managers not only identify what has gone wrong, but also identify what is required to fix the problem. The response to issues will be increasingly automated over time as FDD becomes more sophisticated, freeing up even more of facility managers' time to focus on proactive strategic planning. In the future, prognostics and analytics of multiple large data sets will increase facility managers' ability to look at one system in the context of others and see how components are interacting. As adoption of these new technologies increases, they are transforming the way buildings are managed and enabling facility managers to have a more proactive role in increasing building efficiency and occupant comfort.

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