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Characterization and Survey of Automated Fault Detection and Diagnostic Tools

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Disclaimer

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Executive Summary

Background

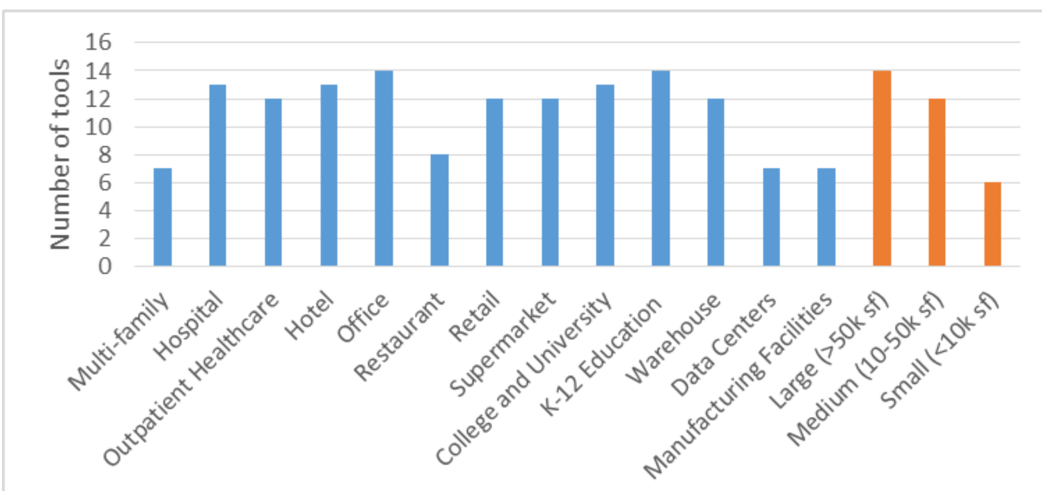
It is estimated that 5%–30% of the energy used in commercial buildings is wasted due to faults and errors in the operation of the control system. Tools that are able to automatically identify and isolate these faults offer the potential to greatly improve performance, and to do so cost effectively. This document characterizes the diverse landscape of these automated fault detection and diagnostic (AFDD) technologies, according to a common framework that captures key distinguishing features and core elements.

Approach

To understand the diversity of technologies that provide AFDD, a framework was developed to capture key elements to distinguish the functionality and potential application of one offering from another. The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings. These 14 technologies largely represent solutions that integrate with building automation systems, that use temporary in field measurements, or that are implemented as retrofit add-ons to existing equipment. To characterize them, publicly available information was gathered from product brochures and websites, and from technical papers. Additional information was acquired through interviews and surveys with the developers of each AFDD tool. The study concludes with a discussion of technology gaps, needs for the commercial sector, and promising areas for future development.

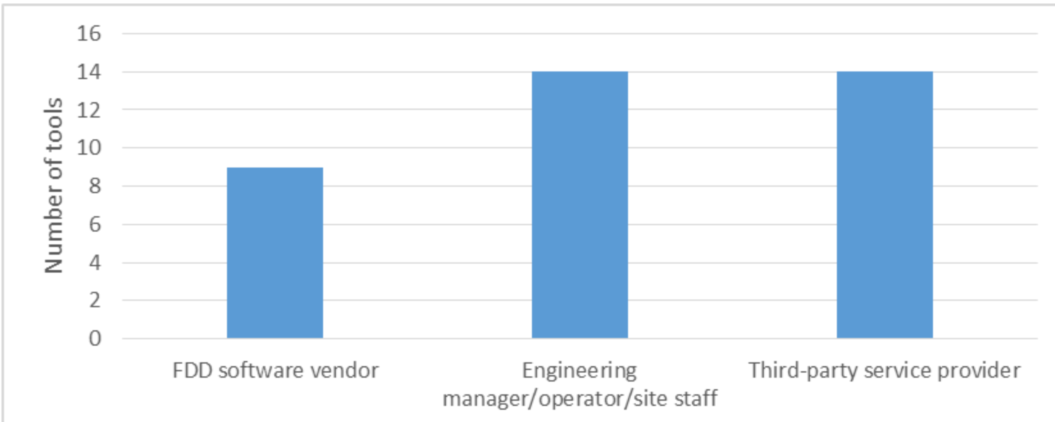
Key Findings

Today's AFDD technologies are being used in nearly all commercial building sectors. Smaller facilities, however, are less commonly served, and when they are it is often through portfolios of small buildings as opposed to single sites.

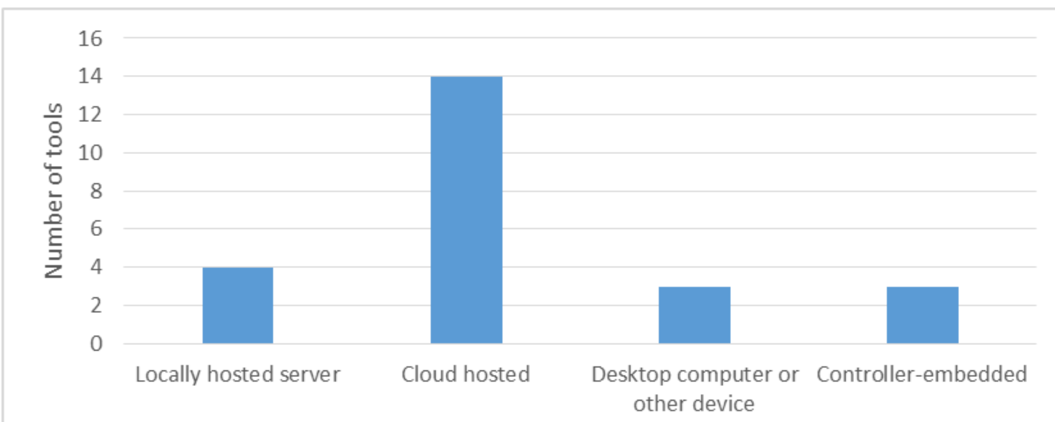


Market presence of surveyed FDD tools

Software-as-a-service models have quickly become the norm for AFDD technologies; even vendors providing on premise and desktop applications also tend to offer SaaS options. A compelling evolution in the industry is seen in the expansion of market delivery of FDD through third-party service providers using the tools as a way to provide value-add to their customers. This expansion offers the potential to increase access to the technology and its associated benefits for a new class of owners who otherwise may not be using it, however third parties' costs may vary significantly and each cost component should be defined in full to be able to compare across delivery options.



Intended users of surveyed AFDD tools



Location of surveyed AFDD tools

While rule-based methodologies to detect and diagnose faults are still heavily used, vendors are beginning to use process history-based techniques. Independent of the FDD methodology used, vendors report a high degree of commonality in the systems and types of faults that their products can cover. That is, coverage of systems and faults is driven more by site data availability than by product offering. Most AFDD tools surveyed accept real-time BAS data and external meters and sensors; many accept historical data from the BAS, and several accept equipment's onboard/ internal measures without going through the BAS. The majority of the AFDD tool vendors surveyed cover major the HVAC systems found in commercial buildings, as well as lighting systems and whole building energy use. Many tools have large libraries that are able to determine at least some types of faults across all systems for whatever data can be provided. Nearly all of the tool vendors surveyed are able to detect faults in the major categories, including: sensors, energy consumption, economizers and ventilation, commercial refrigeration, cooling/heating systems, equipment cycling, scheduling, and lighting or other end uses. Configuration of the technologies does require site-specific tuning. While this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors are often associated with the additional features offered to complement the AFDD, and with the available delivery models. The market offers great diversity in additional analytics and reporting capabilities, integration architectures, and purchase models, making it possible to custom fit the technology to the needs of the organization. While custom solutions are desirable for some portions of the buildings market— such as campuses, enterprises, and large or complex facilities—others may benefit from higher degrees of commoditization.

An important theme in interpreting the findings from this survey is that many products are sold with an emphasis on broad-scale applicability, and in analyzing the features and capabilities across all offerings as whole, there is indeed a high degree of similarity. However, it is critical for prospective technology users to probe providers to understand the precisely what is entailed in a given offering's implementation of a feature of interest. For example, there are many ways to prioritize faults and estimate their impacts, and effective prioritization may be dependent on customer input. Similarly, root cause analysis (diagnosis) may be supported for just a subset of faults, or require manual input from operational staff. Analogously, ease of integration with different makes and vintages of BAS is another critical element of implementation for which "the devil is in the details."

Outstanding Needs

FDD technology is seeing increased uptake in the market, and is constantly developing and evolving. Best practice implementations can deliver significant improvements in energy efficiency, utility expenses, operations and maintenance processes, and operational performance—all with rapid return on investment. However, for the full potential to be realized at scale, a core set of interrelated informational, organizational, and technical needs and barriers must be addressed.

The primary informational barriers for prospective users are rooted in interpreting the value proposition of FDD for their facilities, and in accessing best practices in implementation — for example all-in costs and benefits, effective use of contractors and service providers, and integration with higher level energy management practices. Organizationally, successful implementation of AFDD can be slowed by a need to diverge from existing business practices and norms. While the costs are modest compared to capital projects and can be quickly recovered, decision makers must buy in to an increase in operation and maintenance expenses and be willing to manage a certain degree of risk. Finally, from a technical standpoint, IT and data integration represent one of the largest challenges. Even once data is accessible through cross-system integration, it must be interpreted for use in analytic applications. The current lack of common standards in data, metadata, and semantic representation also poses difficulties in scaling. Lastly, today's AFDD offerings can prove difficult and expensive to apply in smaller commercial buildings.

Future Work

AFDD has matured significantly since its first introduction into commercial buildings. Based on information gathered through this survey and discussion with both vendors and users, several opportunities emerge to further advance the technology. Continued development of algorithms that include machine learning and other promising techniques could reduce tuning needs, simplify configuration, and enhance diagnostic power. Following the trends in other industries, there is also potential to move beyond diagnostics into prognostics and predictive maintenance. Machine-to-machine integration presents further opportunity for advancement to realize pervasive "plug-and-play" functionality, thereby enabling tighter coupling of AFDD with computerized maintenance management systems, meter analytics, and operations and asset management tools. Finally, there are gains to be achieved through the development of corrective and adaptive controls, in combination with tool chains that can ensure that operational design intent is correctly implemented and maintained over the duration of the operational stage in the building lifecycle.

1. Overview

Energy Management and Information Systems (EMIS) comprise a broad family of tools and services to analyze, monitor, and control commercial building equipment and energy use. These technologies include, for example, meter analytics or energy information systems (EIS), some types of automated fault detection and diagnostic tools (AFDD), benchmarking and utility bill tracking tools, and building automation systems. These technologies may encompass uses that include monitoring-based and ongoing commissioning, remote audits and virtual assessments, enterprise monitoring and asset tracking, continuous savings estimation, and energy anomaly detection. There are a wide a wide variety of EMIS products available on the commercial market, and they are increasingly heavily marketed to the energy management community.

It is estimated that 5%–30% of the energy used in commercial buildings is wasted due to faults and errors in the operation of the control system[1, 2, 3]. Tools that are able to automatically identify and isolate these faults offer the potential to greatly improve performance, and to do so cost effectively.

This document characterizes the diverse landscape of technologies that offer AFDD functionality, according to a common framework that captures key distinguishing features and core elements. These technologies can reside on local servers or in the cloud, as well as at the network edge within equipment or controller-embedded solutions.

The primary audience for this document is building owners and operators, who are seeking an understanding of the functionality available in AFDD products and services to inform piloting and procurement decisions. It also may be useful to utility energy efficiency program stakeholders who are interested in emerging technologies to test and pilot for incentive programs. A secondary audience includes developers of AFDD solutions who are looking for information to inform and target their efforts.

In the following sections of this review we present a general overview of FDD and other analytics technology types, followed by a common framework to distinguish among various types of AFDD tools. We then apply this framework to evaluate a sampling of AFDD tools and discuss the findings. The evaluation focused primarily on solutions that integrate with building automation systems, that use temporary in-field measurements, or that are implemented as retrofit add-ons to existing equipment; it did not include OEM-embedded AFDD offerings (although in a few instances these variants are available through the AFDD vendor). We conclude with a discussion of technology gaps, needs for the commercial sector, and promising areas for future development.

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[1] Roth, K. W., D. Westphalen, M. Y. Feng, P. Llana, and L. Quartararo. *Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential.* 2005. Report prepared by TIAC LLC for the U.S. Department of Energy.

[2] Katipamula, S., and M. Brambley. 2005. "Methods for fault detection, diagnostics, and prognostics for building systems – a review, part 1." *HVAC&R Research* 11(1): 3–25.

[3] Fernandez, N., et al. 2017. *Impacts on commercial building controls on energy savings and peak load reduction.* Pacific Northwest National Laboratory. PNNL Report Number PNNL-25985.

2. Introduction to Fault Detection and Diagnostics

FDD is the process of identifying (detecting) deviations from normal or expected operation (faults) and resolving (diagnosing) the type of problem or its location. FDD has been used for decades to great success in industries that include aerospace, nuclear, and industrial applications, and its use in building operation and control applications is growing. In practice, FDD in buildings is most commonly conducted for heating, ventilation, and air conditioning (HVAC) systems, however as a process, FDD is applicable to all systems in the building. Although currently underutilized, FDD is a powerful approach to ensuring efficient building operations.

As further detailed in the characterization framework that follows, AFDD technology may be delivered through a variety of implementation models. The FDD code may be integrated into either server-based software, desktop software, or software that is embedded in an equipment controller. The AFDD algorithms may rely on historical or near-real time data from building automation systems (BAS), from data local to the equipment or controller, from external sensors and meters, or from some combination of these data sources. AFDD software may be used by the building operator or energy manager, or may be delivered through analysis-as-a-service contracts that do not require direct "in-house" use of the technology.

The software tools that offer AFDD may include additional functionality such as energy consumption monitoring and analytics, visualization, benchmarking, reporting of key performance indicators, or fault prioritization and impact assessment. The server-based offerings rely on continuous data acquisition and analysis; these types of AFDD tools are commonly considered part of the broader family of tools called Energy Management and Information Systems (EMIS). Although not within the scope of this document, other EMIS technologies such as meter analytics or energy information systems, automated (HVAC) system optimization, and building automation systems are powerful tools for ensuring persistent low-energy commercial building operations—both at the facility and enterprise levels.

3. FDD Technology Characterization Framework

To understand the diversity of technologies that provide AFDD, a characterization framework was developed to capture key elements that can be used to distinguish the functionality and potential application of one offering from another. Content contained in this framework was developed through review with a subset of providers, and is based on the authors' collective subject matter expertise, knowledge of AFDD technology and its use in commercial building energy management applications. The categories in the framework are defined in the following sections, with characteristics spanning delivery to market, technical capabilities, and additional software functionality.

3.1 Delivery to Market

Company or institution name: The developer of the AFDD technology.

Tool name: The name of the AFDD software or service offering.

Software type: Whether the AFDD is offered as a commercial product or service, or as open source code.

Availability to market: Whether the AFDD is commercially available or still being researched (pre-commercial).

Current markets served: What markets are currently served in terms of:

- Building type (multi-family, hospital, outpatient healthcare, hotel, office, restaurant, retail, supermarket, college and university, K–12 education, warehouse).
- Building size (large [> 50k square feet (sf)], medium [10–50k sf], small [< 10k sf]).

Software location: Whether the AFDD software is cloud hosted, locally hosted on an "on-site" server, located on a desktop computer or other device, or controller-embedded.

Purchase model: Whether the AFDD software is a one-time purchase, software as a service (with monthly or annual fee), or other. Additionally, whether the AFDD software comes with updates and/or periodic maintenance in the initial offering costs, or whether additional purchase is required.

Intended users: Whether the AFDD software is intended for use by the vendor (for analysis-as-a-service), an engineering manager/operator/site staff, and/or a third-party service provider.

Software configuration: Whether the party typically responsible for the AFDD software installation and configuration is the software vendor; an integrator, distributor, or third-party service provider; or an engineering manager/operator/site staff.

Data sources: Whether the AFDD software relies upon data from BAS real-time data (i.e., live, continuous), from BAS historical data (e.g., trend logs, csv, xls), from on-board or internal equipment measures, or from external meters and sensors.

Data ownership: Whether the owner(s) of the AFDD software tool inputs and outputs is the end-customer, the FDD software vendor, and/or a third-party service provider.

FDD method tailoring: Whether the AFDD software requires tailoring of the tuning algorithm parameters and associated thresholds manually or automatically, or whether it is not applicable or unnecessary.

Notification of findings: Whether the AFDD software tool delivers results through a software user interface with fault findings, through a service to the user that includes periodic reports of fault findings, and/or through automated notifications, e.g., via email or text.

3.2 Technical Capabilities

Systems covered: Whether the FDD software has existing libraries and rules for the following systems: air conditioners/heat pumps (including packaged rooftop units), chillers and towers, air handler units (AHUs) and variable air volumes (VAVs), fan coil units (FCUs), commercial refrigeration, lighting, boilers/furnaces, water heaters, and/or whole-building.

Categories of faults detectable: These are broad categories of faults that the AFDD tool is able to detect and potentially diagnose. The fault categories included in this framework include:

- Sensor errors/faults
- Energy consumption (explicit energy use fault)
- Economizers and ventilation
- Control-related pressurization issues
- Commercial refrigeration (related to vapor/compression)
- Space cooling/heating (related to vapor/compression)
- Heating system (boiler, heat exchanger, furnace, etc.)
- Cooling system (chillers, towers, etc.)
- Equipment cycling
- Pump and fan systems
- Scheduling (too little, too long, wrong time, etc.)
- Simultaneous heating and cooling
- Lighting or other end uses

Note that problems such as mechanical failures and departures from setpoint or intended sequences may be included under multiple fault categories in the list above.

Methods/algorithms: These are the categories of analytical methods used in the AFDD software. The schematic diagram below depicts the definition of algorithm types that are used in this framework.

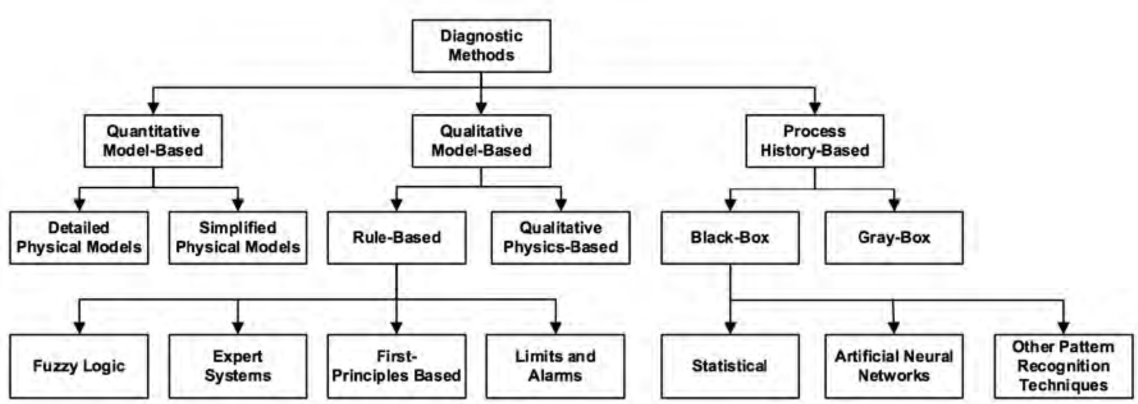

Figure 1. Depiction of algorithm types used in this framework, from Katipamula and Brambley, 2005[2]

As illustrated in Figure 1, FDD methods may be model-based or based purely on process history data. The model-based methods rely upon knowledge of the underlying physical processes and first principles governing the system(s) being analyzed. Quantitative model-based approaches are not yet frequently employed in commercial AFDD tool offerings, however qualitative model-based approaches which include rule-based FDD, have been extensively used in the industry and provide intuitive representations of engineering principles. The process history-based (data-driven) approaches do not rely upon knowledge of first principles, but may leverage some degree of engineering knowledge; they rely upon data from the system in operation. These include statistical regression models, neural networks, and other methods. Process history-based AFDD algorithms are increasingly being explored for use in commercial tool offerings. Although the distinctions between these method types may become blurry (even to developers), AFDD users may have interest in understanding whether a technology uses rules-based techniques versus newer data driven approaches, or less commonly employed first principles – or a combination of several approaches.

Detection and diagnosis capabilities: Whether the AFDD tool is capable of identifying fault presence (reporting a fault without specification of the physical location, severity, or root cause), fault location, fault severity (degree of faultiness as opposed to impact on energy or dollars, which is covered in "additional functionality"), root cause, and/or estimated costs of resolution and payback.

3.3 Additional Functionality

Other features: Additional features of the AFDD tool that are not represented above, and may include:

- Detection of equipment degradation
- Fault prioritization
- Automated work order request system integration
- Assessment of energy impacts
- Conversion of energy impacts to cost impacts
- Assessment of cost impacts other than energy cost, e.g., reduced equipment life
- Meter data analytics
- Time series visualization and plotting
- Key performance indicator (KPI) tracking and reporting
- Longitudinal and cross-sectional benchmarking (within a given portfolio or via ENERGY STAR Portfolio Manager)

4. Technology Characterization Findings

The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings (see the Appendix for a list of those surveyed). These technologies were identified based on factors including:

- Diversity across defining characteristics to illustrate market breadth
- Known use in commercial buildings based on the authors' knowledge of the market and engagement with the community of AFDD users
- Vendor or developer willingness and ability to share information necessary for a full characterization

It is important to emphasize that inclusion in this survey does not indicate endorsement, and conversely, absence from the survey does not indicate non-endorsement.

To characterize the technologies, publicly available information was gathered from product brochures and websites, and from technical papers. Additional information was acquired through interviews and surveys with the vendors and developers of each AFDD tool. The information that was acquired was therefore based on self-reporting from the technology provider. It was not within the scope of this effort to independently verify reported functionality and characteristics of each technology that is included. Moreover, as the market is constantly evolving and technologies are continuously modified, these market findings represent a snapshot in time. Although specific offerings may evolve, it is expected that the characterization framework itself will remain a viable tool to distinguish key AFDD technology elements well into the future.

The tables in the Appendix provide a summary of the capability of each tool surveyed, with respect to each category in the characterization framework.

4.1 Delivery to Market

All tool vendors surveyed offered proprietary, commercially available software and/or hardware. However, several of the software vendors noted that they provide an open application programming interface (API) to support integration with third-party applications.

The markets currently served by the AFDD tool vendors are represented in Figure 2. Multi-family, restaurant, data centers, and manufacturing facilities are less commonly served, with a mostly even coverage of other sectors. In addition to the market segments shown in the figure, several tool vendors noted additional facility types such as industrial subsectors, arenas, multi-event facilities, and correctional facilities. The technologies are commonly used in large and medium facilities, with less penetration in smaller buildings. Several tool vendors also noted that they do not serve a particular building size and that their product would be applicable to any size building.

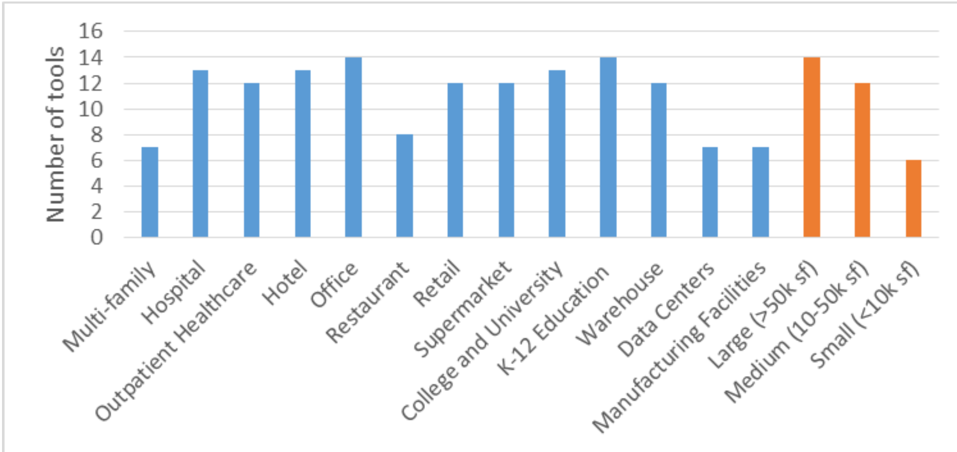

Figure 2.Market presence of surveyed FDD tools

As shown in Figure 3, the software for all 14 tool vendors can be cloud hosted; eight of them offer that as the only option. Additionally, four AFDD tools can be installed on a locally hosted on-site server, and three can be located on a desktop computer or other device (such as a handheld device). Three can be controller-embedded, reflecting emerging variants in software delivery that can entail relationships with OEMs.

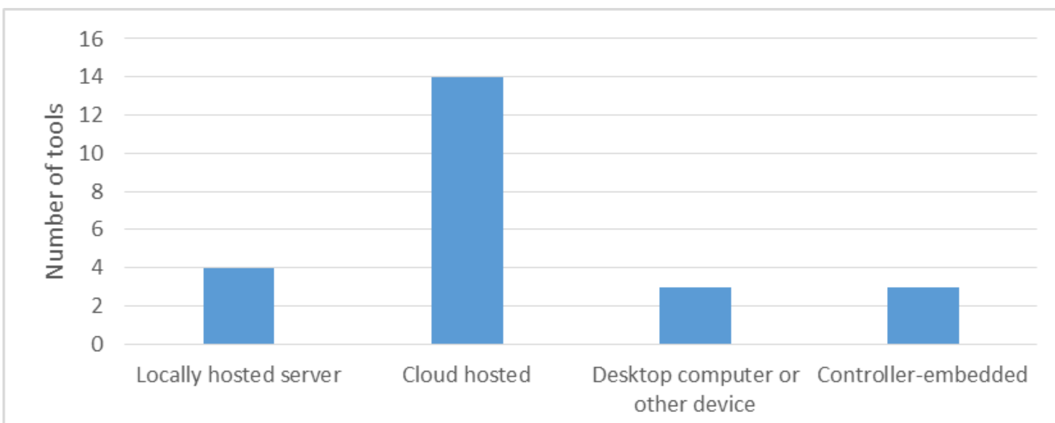

Figure 3. Software location

AFDD tool vendors offer a wide range of variability in purchase models. Many vendors noted that there is no standard, and that often the purchase model is tailored to what the customer wants. Typically tools that are hosted on the cloud offer a software-as-a-service (SaaS) model with ongoing updates and maintenance included for either an annual or a monthly fee. Maintenance and updates may come bundled or optionally in an upfront fee, or can be deferred for later purchase.

As reflected in the tallies in Figure 4, all of the AFDD tool vendors surveyed have multiple intended users. The traditional model of in-house technology used by the end customer is still prevalent—all vendors surveyed listed engineering manager/operator/site staff as an intended user. However, tools are increasingly being used by and resold by third-party service providers as a value-add to customers, with all of the AFDD tool vendors surveyed also listing a third-party service provider as an intended user. Nine vendors provide analysis-as-a-service directly to their clients and are therefore an intended user of the tool. This is expected to grow as the market matures and alternative business models are explored by the industry.

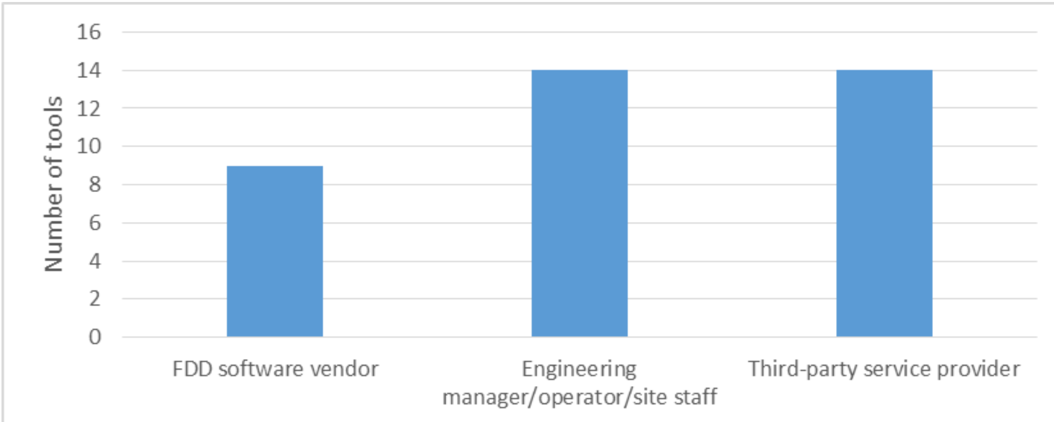

Figure 4. Intended Users

The majority of the AFDD tools are installed and configured by some combination of the software vendor, an integrator/distributor/third-party service provider, and the engineering manager/operator/site staff, as shown in Figure 5. In most cases, the vendor plus a third party do the configuration, working from owner requirements. In some cases multiple parties are required for the installation, and in some cases the vendor offers several options for who does the installation.

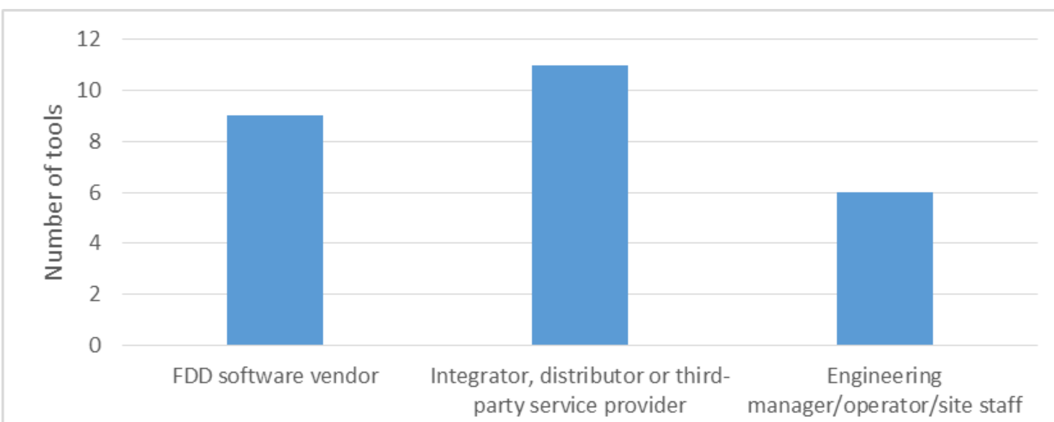

Figure 5. Parties involved in software configuration

There is a range of input data that are required by AFDD tools and a range of data that they can accept, as shown in Figure 6. Most of the tools take in real-time BAS data, which would be expected, given the large number of cloud-based solutions that serve as a BAS overlay. Eleven tools are also able to utilize historical data from the BAS. Most of the tools are also able to utilize external meters and sensors. Three tools are able to utilize equipment's onboard/ internal measures without going through the BAS. Typically not all of the data points that *can* be processed by the tool are required, and the technologies operate based on the data that are available. Though the tool vendor may have a short list of critical points, additional data are used to enhance the spectrum of diagnostics that can be performed.

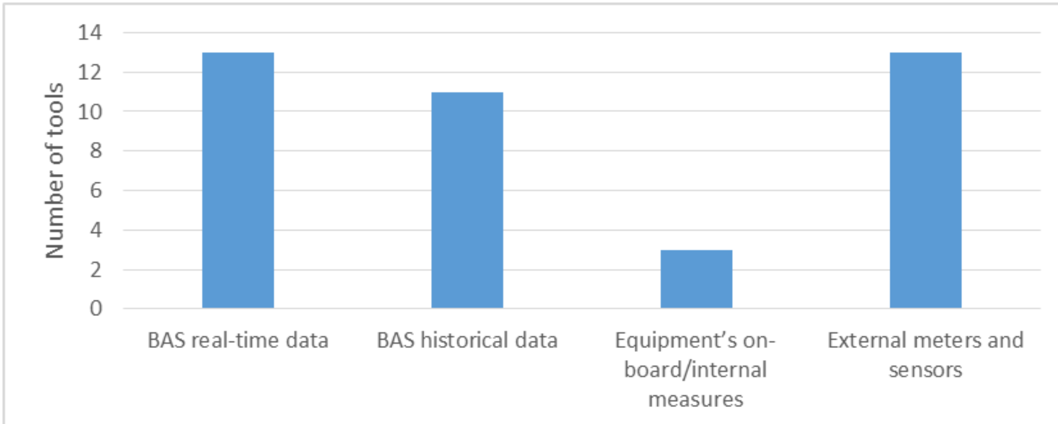

Figure 6. Data sources for surveyed FDD tools

All AFDD tool vendors note that primarily, the customer owns the data. Additionally, two vendors noted that they themselves also have ownership over the data and one other tool vendor noted that a third-party service provider has ownership over the data. Several tool vendors noted that they retain the right to use aggregate and anonymous data for benefit of all their users; for example, to provide peer benchmarking analyses.

All 14 tools require some degree of tuning or tailoring algorithm configuration and implementation. While none offer fully automated tuning, six vendors noted that they provide automated routines and/or GUIs to streamline the process. At least one tool comes with a fault library with default thresholds, with which the customer may subsequently tune parameters or hire consultants to help.

All of the AFDD tool vendors provide access and viewing of fault findings through a software interface, as shown in Figure 7. In addition to user-facing GUIs, the majority of offerings surveyed also provide services to periodically output reports of fault findings. All but two of the tools provide automated notifications via text, e-mail, or even other novel communications options such as tweets. Several tool vendors have the capability to have reports sent via e-mail at user-defined intervals (daily, weekly, monthly) and on customer demand.

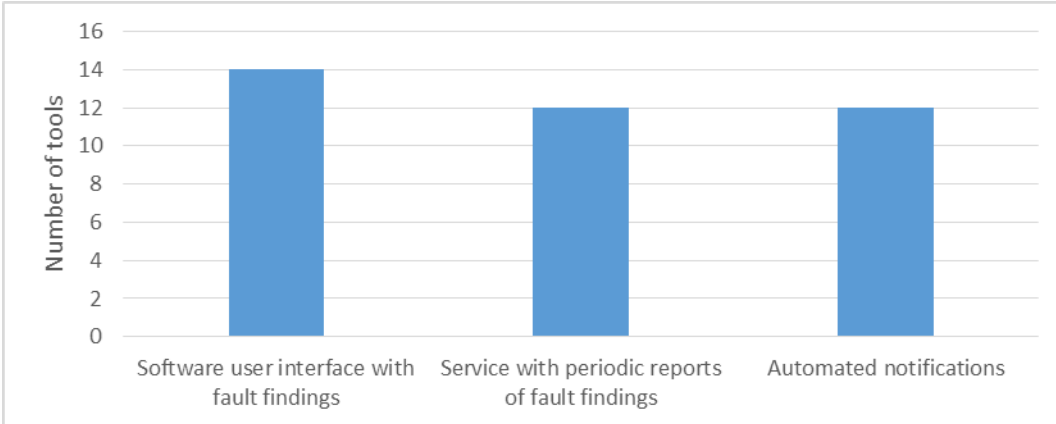

Figure 7. Notification of findings

4.2 Technical Capabilities

As seen in Figure 8, the majority of the AFDD tool vendors surveyed cover most of the systems that were included in the survey (AC/heat pump which includes packaged rooftop units, chillers and towers, AHU and VAV, FCUs, commercial refrigeration, lighting, boilers/furnaces, water heaters, and whole-building). Many tools have large libraries that are able to determine at least some types of faults across all systems for whatever data can be provided. Several vendors reported that they additionally include energy recovery ventilators (ERVs), other terminal units besides VAV boxes, solar panels, industrial processes, variable refrigerant flow (VRF) systems, BAS controls, cogeneration, and manufacturing equipment.

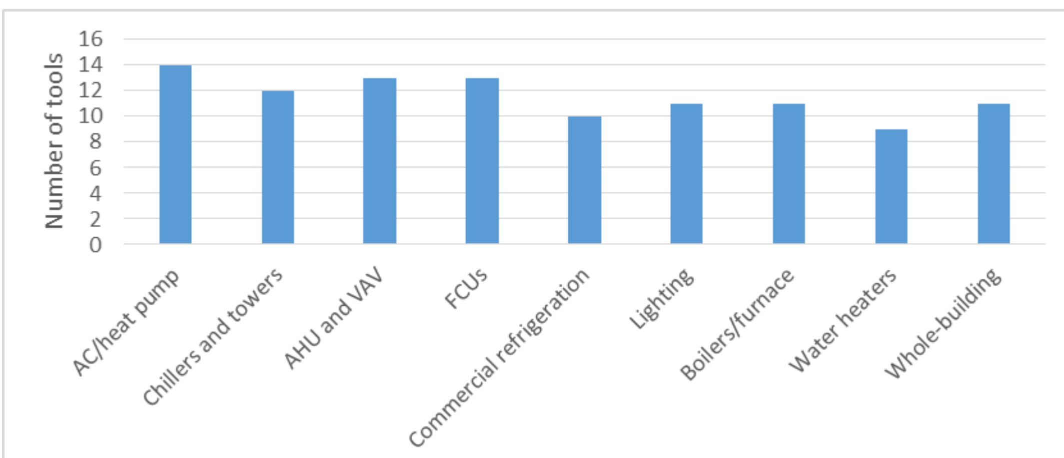

Figure 8. Systems covered

Nearly all of the tool vendors surveyed are able to detect faults in the majority of the fault categories in the survey: sensor errors/faults, energy consumption, economizers and ventilation, control-related pressurization issues, commercial refrigeration, space cooling/heating, heating system, cooling system, equipment cycling, pump and fan systems, scheduling, simultaneous heating and cooling, and lighting or other end uses. Many tools have large libraries that are able to determine at least some types of faults for whatever data can be provided. See Figure 9 for details.

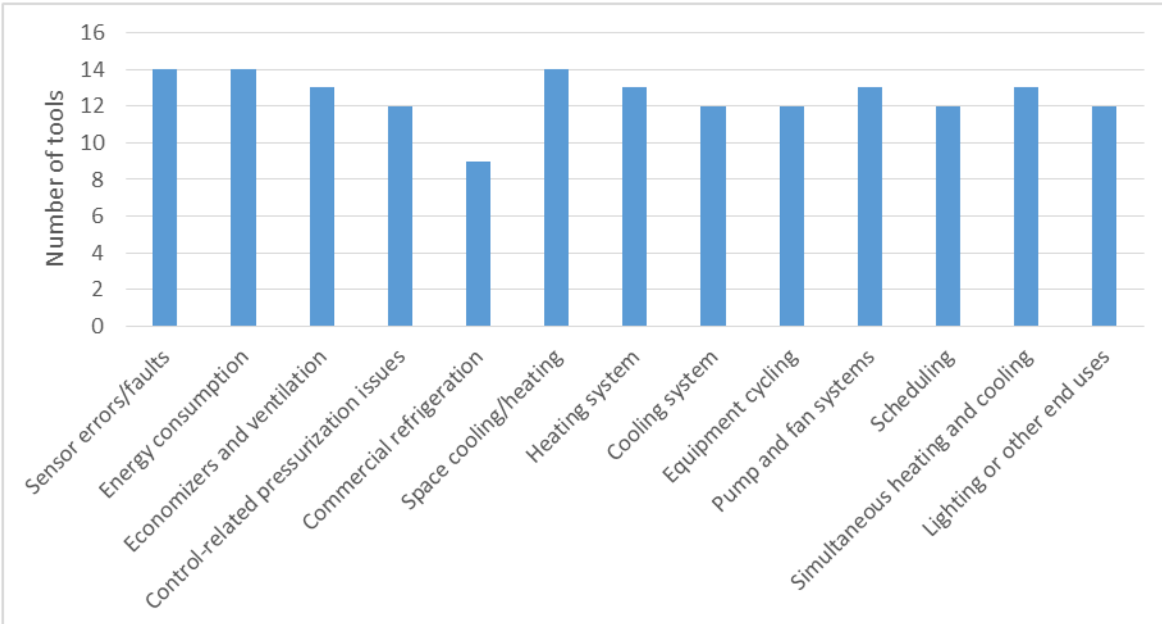

Figure 9. Categories of detectable faults

Most of the tools (12 out of 14) use rule-based algorithms, the majority of which apply some combination of expert systems, first principles-based, and limits and alarms. Many of the rule-based tools are supplemented with other approaches, and in one case the offering is a platform that is most commonly programmed and configured to deliver rule-based algorithms, but also includes machine learning functions. Three tools use black-box process history-based approaches; one of these also uses a gray-box approach. Two tools use quantitative model-based approaches. Figure 10 illustrates these findings graphically—dark shading indicates approaches used by ten or more tools, medium shading indicates approaches used by two or three tools, and light shading indicates approaches used by one or no tools.

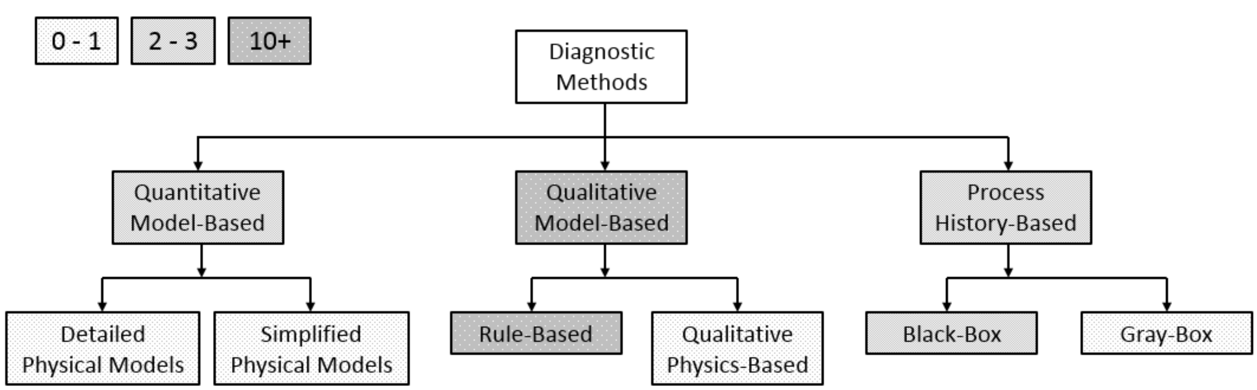

Figure 10. Methods and algorithms

As shown in Figure 11, all vendors surveyed reported the ability to identify fault presence as well as physical fault location. All but one tool is able to identify potential root causes. Depending on the specific fault identified, root case identification may be more or less precise, or in some cases, not possible. In addition, all but one reported some quantification of fault severity, e.g., degree of leakage. The degree of faultiness may be determined based on the frequency of a fault, fault magnitude (e.g., how far a point is away from setpoint), and fault duration. Several tools associate fault severity with assessment of the degree to which energy, energy cost, comfort, and maintenance costs are affected. At least one of these tools prioritizes the faults, then displays only one fault at a time to the user.

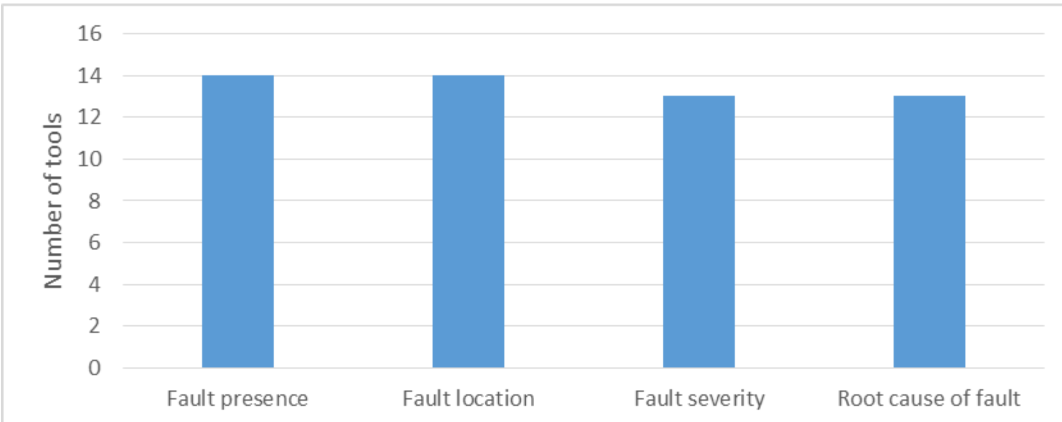

Figure 11. Detection and diagnosis capabilities

4.3 Additional Functionality

AFDD tools are commonly delivered with many supplementary features. Out of the tools surveyed, the most common features were time series visualization and plotting, quantification of energy impacts, and fault prioritization, as shown in Figure 12. Other very common features were equipment degradation, conversion of energy impacts to cost impacts, KPI tracking and reporting, automated work order request system integration, and meter data analytics. Less common but still prevalent features were cost impacts other than energy cost (such as the cost of pending equipment failure), longitudinal and cross-sectional benchmarking, and estimated cost of fault resolution and payback.

In addition, tool vendors noted a number of other features, including feedback for load management and demand response applications, verification of corrective actions, savings measurement and verification (M&V), equipment level M&V, asset data and service history, and issue-tracking systems. These other features were not exhaustively reviewed in the survey (or Tabulated findings in the Appendix) but are important complements to the AFDD capabilities.

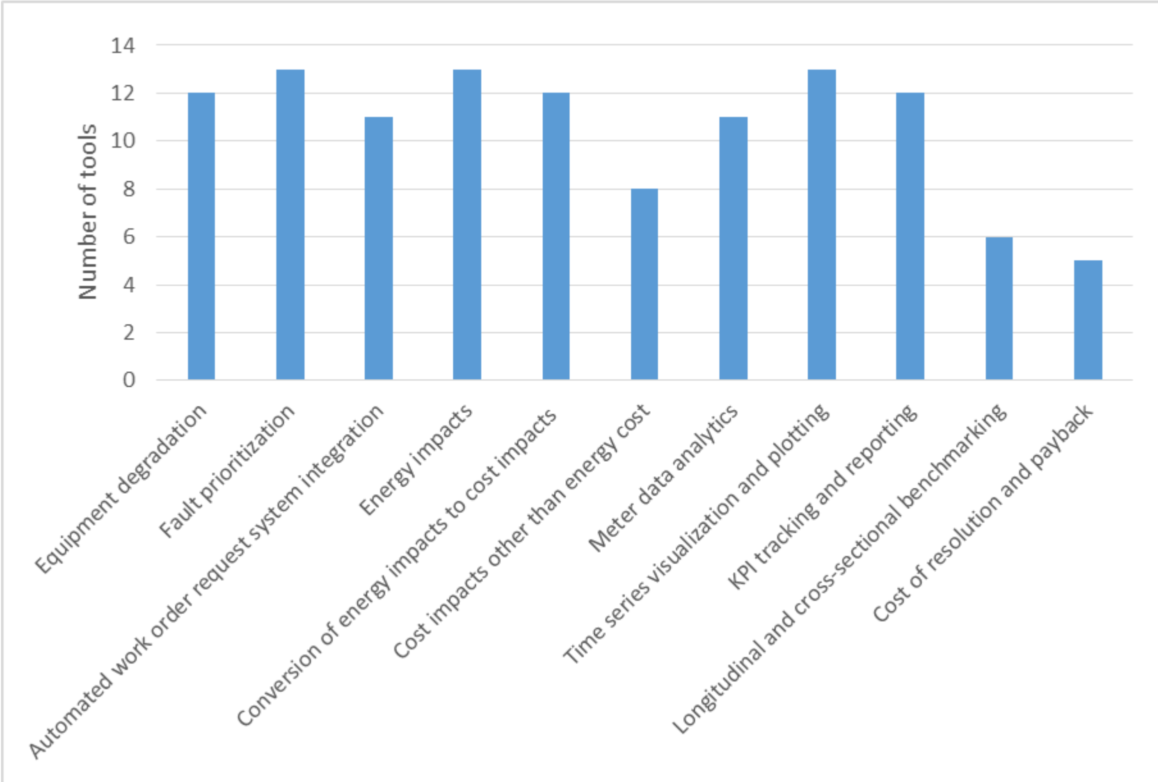

Figure 12. Relative frequency of a selected set of additional features of AFDD tools

5. Industry Needs and Future Development

This survey focused on AFDD solutions that integrate with building automation systems, that use temporary in-field measurements, or that are implemented as retrofit add-ons to existing equipment. As indicated in the findings, today's AFDD technologies are being used in nearly all commercial building sectors. Smaller facilities, however, are less commonly served, and when they are it is often through portfolios of small buildings as opposed to single sites. Cost effectiveness and complexity of implementation may vary as the technology is applied to different sectors and building sizes. For example, with a historic emphasis on HVAC systems and larger buildings, solutions for built-up systems may be simultaneously more developed, yet also more complex than those for packaged systems.

Software-as-a-service models have quickly become the norm for AFDD technologies; even vendors providing on-premise and desktop applications also tend to offer SaaS options. A compelling evolution in the industry is seen in the expansion of market delivery of FDD through third-party service providers using the tools as a way to provide value-add to their customers. Illustrated in Figure 13, these third-party services may cover a spectrum of activities. This is in contrast to earlier models that relied on in-house direct organizational use, and also from analysis-as-a-service provided by the AFDD vendor. This expansion offers the potential to increase access to the technology and its associated benefits for a new class of owners who otherwise may not be using it, however third parties' costs may vary significantly and each cost component should be defined in full to be able to compare across delivery options.

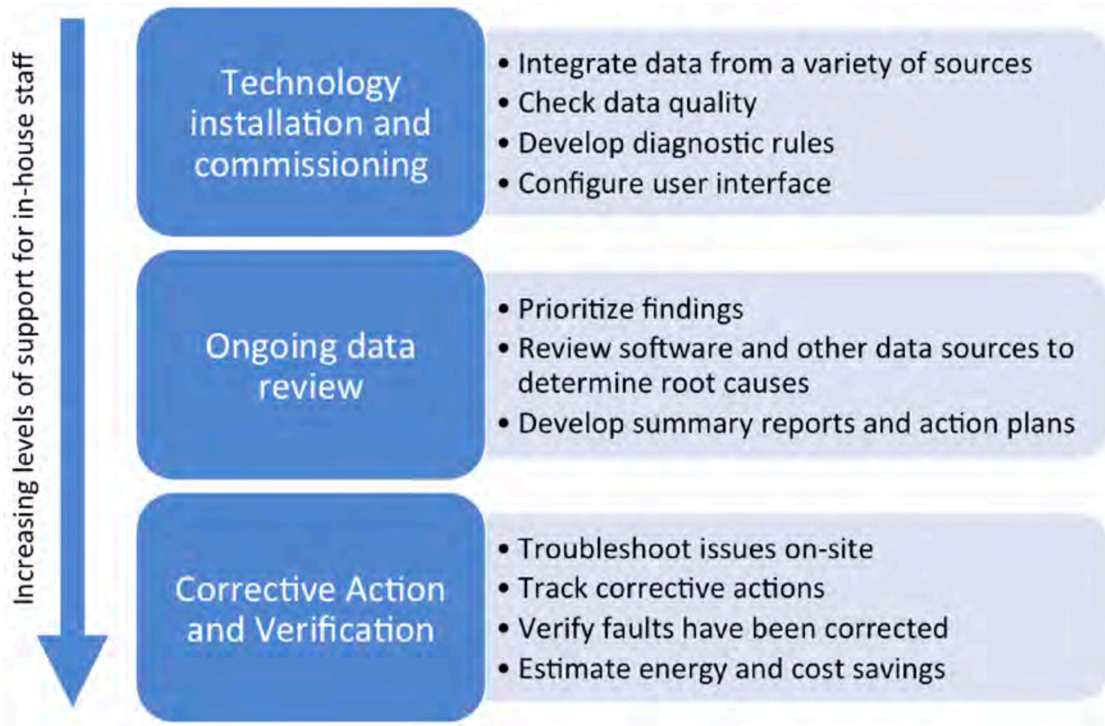

Figure 13. A spectrum of analytics-focused activities that service providers may offer their customers

While rule-based methodologies to detect and diagnose faults are still the norm, vendors are beginning to use process history-based techniques. Independent of the FDD methodology used, vendors report a high degree of commonality in the systems and types of faults that their products can cover. That is, coverage of systems and faults is driven more by site data availability than by product offering. Configuration of the technologies does require site-specific tuning, which may be conducted by vendors and service providers with varying degrees of involvement from site staff. While this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors are often associated with the additional features offered to complement the AFDD, and with the available delivery models. The market offers great diversity in additional analytics and reporting capabilities, integration architectures, and purchase models, making it possible to custom fit the technology to the needs of the organization. While custom solutions are desirable for some portions of the buildings market— such as campuses, enterprises, and large or complex facilities—other portions of the market may benefit from higher degrees of commoditization.

An important theme in interpreting the findings from this survey is that many products are sold with an emphasis on broad-scale applicability, and in analyzing the features and capabilities across all offerings as whole, there is a high degree of similarity. However, actual implementation needs can differ widely from one application case to another. Moreover, it is critical for prospective technology users to probe providers to understand the precisely what is entailed in a given offering's implementation of a feature of interest. For example, there are many ways to prioritize faults and estimate their impacts, ranging from those that rely upon static assumptions of fault persistence versus intermittence, to those that rely upon more dynamic calculations of concurrent operational conditions – and effective prioritization may be dependent on customer input. Similarly, root cause analysis (diagnosis) may be supported for just a subset of faults, or require manual input from operational staff. Analogously, ease of integration with different makes and vintages of BAS is another critical element of implementation for which "the devil is in the details."

FDD technology is seeing increased uptake in the market, and is constantly developing and evolving. Best practice implementations can deliver significant improvements in energy efficiency, utility expenses, operations and maintenance processes, and operational performance—all with rapid return on investment (see the Smart Energy Analytics Campaign Year 1 Report[4] for a snapshot of EIS, FDD and ASO performance and cost). However, for the full potential to be realized at scale, a core set of interrelated informational, organizational, and technical needs and barriers must be addressed.

Informational:

1. Prospective users remain challenged in interpreting the value proposition of FDD for their facilities. Common questions include: what will it really take to make this work for my buildings? What will the all-in costs and benefits be, up-front, and in the long-term? How do I navigate this developing market with numerous evolving players and product options?
2. Prospective users also face more specific implementation questions such as: What is the distinction between automated fault detection and diagnostics (AFDD) and BAS alarms, and which products support one versus the other? What are best practices for tuning and avoidance of false positives? What is the benefit of integrating AFDD within higher-level energy management practices such as strategic energy management and ongoing monitoring-based commissioning? How do I best integrate the support of contractors and service providers with in-house activities?

[4] Smart Energy Analytics Campaign. Synthesis of year 1 outcomes in the Smart Energy Analytics Campaign [Internet]. 2017 [accessed on September 25, 2017]. Available from: https://smart-energy-analytics.org/

Organizational:

3. Successful implementation of AFDD can be slowed by a need to diverge from existing business practices and norms. While the costs are modest compared to capital projects and can be quickly recovered, decision makers must buy in to an increase in operation and maintenance expenses and be willing to manage a certain degree of risk. Translation of information into action requires allocation of resources for staff time and training to act upon on identified fixes; it also requires effective operational response processes.

Technical:

4. While improving, IT and data integration represent one of the largest barriers to scale. It is complex, expensive and crosses organizational business units, and communications infrastructures are not easily leveraged for installation of analytics technologies.
5. Once data is accessible through cross-system integration, it must be interpreted for use in analytic applications. The current lack of common standards in data, metadata, and semantic representation also poses difficulties in scaling.
6. Similar to many efficiency solutions, today's AFDD offerings can be difficult and expensive to apply in smaller commercial buildings. Smaller facilities do not commonly have building automation systems or energy management staff and present much tighter payback constraints due to smaller energy expenditures.

A number of academic, industry, utility, and federal efforts are seeking to address these barriers. These collective efforts are far too varied and numerous to comprehensively describe, however, a few examples from current work sponsored by the U.S. Department of Energy (DOE) are provided as an illustration.

- The University of New Haven is conducting a public-facing field evaluation[5] of approximately 10 AFDD solutions to quantify technology costs and benefits, and is partnering with the utility community to inform the development of incentive programs for scaled regional deployment.
- The National Renewable Energy Laboratory (NREL) is conducting early-stage development of AFDD solutions for small commercial facilities that are based on simulation modeling and smart meter data.[6]
- Lawrence Berkeley National Laboratory (LBNL) is administering the Smart Energy Analytics Campaign[7] to provide technical assistance to AFDD and other analytics users, track gaps and benefits, and synthesize barriers.

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[5] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Department of Energy announces scaling up the next generation of building efficiency packages funding awards [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://energy.gov/eere/buildings/articles/department-energy-announces-scaling-next-generation-building-efficiency

[6] Frank, S., et al. 2016. Hybrid model-based and data-driven fault detection and diagnostics for commercial buildings. *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings.*

[7] Smart Energy Analytics Campaign. Smart Energy Analytics Campaign [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://smart-energy-analytics.org/

- LBNL and NREL are conducting public-facing multi-site field evaluations of technologies for rooftop unit AFDD and combined FDD/HVAC optimization.[8] Performance results are intended to inform the market at large, with a particular focus on public and private sector portfolio owners.

AFDD has matured significantly since its first introduction into commercial buildings. Based on information gathered through this survey and discussion with both vendors and users, several opportunities emerge to further advance the technology. Some of these are technical development challenges, and some strongly tied to the interplay between market demand and business choices concerning standardization and interoperability.

Continued development of algorithms that include machine learning and other promising techniques could reduce tuning needs, simplify configuration, and enhance diagnostic power. Following the trends in other industries, there is also potential to move beyond fault diagnostics into controls optimization, prognostics, and predictive maintenance. Integration of physics-based models to complement data-driven approaches holds promise to increase diagnostic power and support predictive analytics.

Machine-to-machine integration presents further opportunity for advancement. For example, truly pervasive "plug-and-play" functionality is still being developed, as are solutions to automatically extract and semantically interpret data across diverse systems and data types. The ability to interface AFDD tools with computerized maintenance management systems (CMMS) is just beginning to be explored, and will streamline the process of operationalizing action-taking based on the findings from analytics tools. Similarly, the practice of energy management will be enhanced through an ability to more tightly couple today's disparate systems and platforms with more pervasive data and connectivity for controls optimization, FDD, site and portfolio meter analytics, and operations and asset management. While an "all in one" tool is not likely, nor necessarily optimal, some convergence for users would be beneficial.

Finally, there are gains to be achieved through the development of corrective and adaptive controls, in combination with tool chains that can ensure that operational design intent is correctly implemented and maintained over the duration of the operational stage in the building lifecycle.

[8] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. BuildingIQ Inc: Predictive Energy Optimization [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://energy.gov/eere/buildings/downloads/buildingiq-inc-predictive-energy-optimization

Appendix

Table 1 summarizes aspects of market delivery for each tool surveyed, and Table 2 summarizes their AFDD technical capabilities and additional software features.

Table 1. Market delivery aspects of each tool surveyed

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
SkySpark (platform)	SkyFoundry	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium, Small	Cloud hosted, Desktop computer or other device, Controller-embedded	One time purchase with maintenance included; SaaS through partners	FDD vendor, Site staff, Third-party provider	Third-party provider; Site staff	BAS real-time and historical data, Equipment on-board/internal measures, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications
SkySpark (implementn.)	CBRE|ESI	Hospital, Office, Retail, Supermarket, College and Univ, K-12 Ed	Large, Medium	Locally hosted server, Cloud hosted	SaaS. Optional updates and maintenance after first year	Site staff, Third-party provider	Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer, FDD vendor, Third-party provider	Manual	Software user interface, Service with periodic reports, Automated notifications
True Analytics	Ecorithm	Multi-fam., Hospital, Hotel, Office, College and Univ, K-12 Ed, Warehouse	Large	Cloud hosted	SaaS. Updates and maintenance included	Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data	End-customer	Manual and Automated	Software user interface, Service with periodic reports
Clockworks	KGS	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium	Cloud-hosted (via platform-as-a-service)	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
Kaizen	CopperTree Analytics	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium, Small	Cloud hosted	SaaS. Use partners as value-added resell distributers Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
BuildPulse	BuildPulse Inc.	Hospital, Outpat. Health., Hotel, Office, Retail, College and Univ, K-12 Ed	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	Third-party provider, Site staff	BAS real-time data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
Analytika	Cimetrics	Hospital, Outpat. Health., Hotel, Office, Supermarket, College and Univ, K-12 Ed, Warehouse, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor	BAS real-time and historical data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
Niagara Analytics 2.0	Tridium	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Locally hosted server, Cloud hosted, Controller-embedded	One time purchase with optional updates and maintenance	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, Equipment on-board/internal measures, External meters and sensors	End-customer	Manual and Automated	Software user interface, Automated notifications
IntelliCommand	JLL	Hospital, Outpat. Health., Hotel, Office, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	Site staff, Third-party provider	FDD vendor	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
Balance	EEI	Multi-fam, Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included.	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer, FDD vendor	Manual	Software user interface, Service with periodic reports
Facility Analytix	ICONICS	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large	Locally hosted server, Cloud hosted	One-time purchase or SaaS. Maintenance included, updates optional	Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications
eIQ	Transformative Wave	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Automated notifications
ClimaCheck Onsite/ ClimaCheck Online	ClimaCheck	Multi-fam, Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Locally hosted server, Cloud hosted, Desktop computer or other device	Onsite: One-time purchase. Optional updates Online: Updates and maintenance included.	FDD vendor, Site staff, Third-party provider	Third-party provider, Site staff	BAS real-time data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
HVAC Service Assistant, SA Mobile, Onboard controller	Field Diagnostic Services	Multi-fam, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, K-12 Ed, Warehouse, Data Centers	Large, Medium, Small	Cloud hosted, Desktop computer or other device, Controller-embedded	One-time purchase or SaaS. Updates included	Site staff, Third-party provider		Equipment on-board/internal measures, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Table 2. Technical capabilities and additional features of each tool surveyed

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
SkySpark	SkyFoundry	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based. Platform supports full programmability of rules and includes machine learning functions for use in FDD algorithms.	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
SkySpark (implementn.)	CBRE|ESI	AC/HP, Chillers & towers, AHU & VAV, FCU, Lighting, Boilers/furnace, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
True Analytics	Ecorithm	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Qual. Model-based, Rule-based, Expert Systems, First Principles-based, Machine learning techniques, fast-sampling algorithms, and the spectral method.	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Energy impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking
Clockworks	KGS	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Simplified Physical Models, Expert Systems, First Principles-based, Limits and Alarms, Statistical	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
Kaizen	CopperTree Analytics	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based. Includes an open library of rules for users to download, publish and share	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting
BuildPulse	BuildPulse Inc.	AC/HP, Chillers & towers, AHU & VAV, FCU, Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Qualitative model	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
Analytika	Cimetrics	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Quant. Model-based, Qual. Model-based, Rule-based, Expert Systems, First Principles-based, Limits and Alarms, Process History-based, Black Box, Statistical, Gray Box	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking
Niagara Analytics 2.0	Tridium	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Limits and Alarms	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Cost of resolution and payback
IntelliCommand	JLL	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Limits and Alarms, Statistical, Other Pattern Recognition Techniques	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
Balance	EEI	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Expert Systems, First-Principles Based	Fault presence, location, severity	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Cost of resolution and payback
Facility Analytix	ICONICS	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, First Principles-based, Limits and Alarms	Fault presence, location, severity, root cause	Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting
eIQ	Transformative Wave	AC/HP	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Pump & fan systems, Sim. htg. & clg.	Rule-based, Expert Systems, Limits and Alarms	Fault presence, location, root cause	Fault prioritization, Energy impacts, Energy cost impacts, Time series visualization
ClimaCheck Onsite/ ClimaCheck Online	ClimaCheck	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig.	Sensor errors, Energy consumption, Econ. & vent., Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Thermodynamic Evaluation, Energy Signatures	Fault presence, location, severity, root cause	Equip degradation, Energy impacts, Energy cost impacts, Time series visualization, KPI tracking and reporting
HVAC Service Assistant, SA Mobile, Onboard controller	Field Diagnostic Services	AC/HP, AHU & VAV, FCU	Sensor errors, Energy consumption, Space Clg./Htg.		Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order