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Commercial Fault Detection and Diagnostics Tools: What They Offer, How They Differ, and What's Still Needed

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ABSTRACT

It is estimated that 5%–30% energy use in commercial buildings is wasted due to faults and errors in operations. Automated fault detection and diagnostics (AFDD) technologies can address this waste by identifying (detecting) deviations from normal or expected operation (faults), and resolving (diagnosing) the type of problem or its location, minimizing the need for complex manual analysis of operational data. Although currently underutilized, AFDD is a powerful approach to ensuring efficient building operations. AFDD offers the potential to greatly improve performance, and to do so cost effectively. There is currently a diverse landscape of AFDD technologies on the market, but no common framework exists to characterize such tools, or distinguish one offering from another. It is difficult to determine from vendor websites and marketing materials key technology features and capabilities, or the overall state of the technology.

In this paper, we present an AFDD characterization framework, and findings from applying the framework to survey over a dozen technologies from today's market. This paper outlines the current state of the market, as well as outstanding needs in the industry, derived from direct engagement of, and technical assistance provided to users of AFDD technology. A core set of interrelated informational, organizational, and technical needs and barriers that must be addressed to realize the full potential of AFDD at scale are identified. Lastly, based on information gathered through a survey and discussion with both vendors and users, several opportunities to further advance the technology are discussed.

Introduction

In commercial buildings, it is estimated that annual building energy use can be cut by an average of 29%, (or ~4-5% of overall national energy consumption), through corrections to existing buildings controls infrastructure and resulting improvements to operating efficiency (Fernandez, 2017). Automated fault detection and diagnostics (AFDD) addressed a subset of this savings potential, using building operational data to identify the presence of faults and isolate their root causes. Over the last three decades the development of AFDD methods for building heating ventilation and air conditioning (HVAC) systems has been an area of active research. Well-cited review publications in the HVAC FDD area include two International Energy Agency Annex Reports (Hyvarinen et al. 1996, Dexter et al. 2001) and literature reviews by Katipamula et al. (2005a, 2005b) and Kim et al. (2018).

Kim and Katipamula (2018) indicated that since 2004, over 100 AFDD research studies associated with building systems have been published. A diversity of techniques are used for

AFDD spanning physical models (Bonvini et al. 2014, Muller et al. 2013), black box (Jacob 2010, Wang 2010), grey box (Sun et al. 2014, Zogg et al. 2006), and rule-based approaches (Bruton 2014, House 2001) with considerable discussion concerning their relative pros and cons. Although currently underutilized, AFDD is a powerful approach to cost-effectively ensure efficient building operation, and AFDD products represent one of fastest growing technology markets in technologies for building analytics. There are well over 20 AFDD products available in U.S. and new software products continue to enter the market (Smart Energy Analytics Campaign 2017).

As further detailed in the characterization framework discussion 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.

One challenge to those seeking to adopt the AFDD technology is that across the landscape of market solutions, it is difficult to determine from vendor websites and marketing materials key technology features and capabilities, or the overall state of the technology. In response, this paper presents a framework to understand the diverse landscape of technologies that offer AFDD functionality, including key elements to distinguish the functionality and potential application of one offering from another. This AFDD characterization framework was applied to evaluate a sampling of AFDD tools and gain insight into the state of today’s technology. 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; the assessment did not include original equipment manufacturer (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.

AFDD 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 of 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 span delivery to market, technical capabilities, and additional software functionality, and are described below:

Delivery to Market

Company and tool name: The developer of the technology and name of the AFDD offering.

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

Availability to market: Whether the product is commercially available or pre-commercial.

Current markets served:

- 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; whether the software comes with updates and/or periodic maintenance in the initial offering costs, or whether additional purchase is required.

Intended users: Whether the software is intended for use by the vendor (analysis-as-a-service), an engineering manager/operator/site staff, 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 real-time BAS data (i.e., live, continuous), from historical BAS data (e.g., csv, xls trend logs), 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 software requires tailoring/tuning of algorithm parameters and 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.

Technical Capabilities

Systems covered: Whether the AFDD software has existing libraries and rules for some of the most common building systems.

Categories of faults detectable: Broad categories of faults that the AFDD tool is able to detect and potentially diagnose.

Methods/algorithms: These are the categories of analytical methods used in the AFDD software. 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 governing first 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 categories are detailed in Katipmaula (2005a).

Detection and diagnostics capabilities: Whether the 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,), root cause, and/or estimated costs of resolution and payback.

Additional Functionality

Other features: Additional features of the AFDD tool that are otherwise not represented.

Technology Characterization Findings

The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings. 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
- Developer ability to share information necessary for a full characterization

It is important to emphasize that inclusion in this survey does not indicate product endorsement, and conversely, absence from the survey does not indicate non-endorsement. For information on the offerings evaluated and product-specific findings, see Granderson et al. 2017.

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 developers of each AFDD tool. The information that was acquired was therefore based on self-reporting from the technology provider. As the market is constantly changing, these 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.

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 1. Multi-family, restaurant, data centers, and manufacturing facilities are less commonly served, with a mostly even coverage of other sectors. In addition to those shown in the figure, several vendors noted additional facility types such as industrial subsectors, arenas, 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.

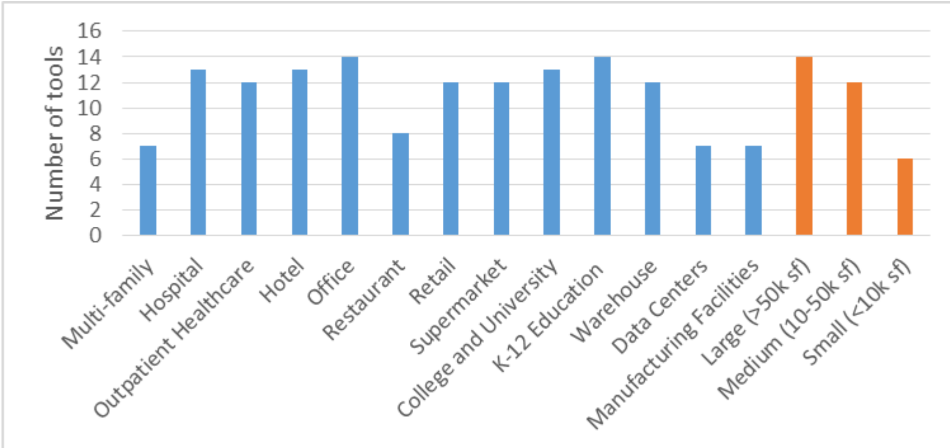

Figure 1. Market presence of surveyed AFDD tools

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. AFDD tool vendors offer a wide range purchase models. Many 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.

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, with all of the vendors surveyed also listing a third-party service provider as an intended user. Nine vendors provide analysis-as-a-service directly to their clients. This is expected to grow as the market matures and alternative business models are explored by the industry.

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. 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.

There is a range of input data that are required by AFDD tools and a range of data that they can accept. All but one of the tools take in real-time BAS data, which would be expected, given that the evaluation mostly comprised cloud-based solutions that serve as a BAS overlay. Eleven tools are also able to utilize historical data from the BAS, and all but one are 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.

All AFDD tool vendors note that primarily, the customer owns the data. Additionally, two vendors noted that they 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.

While none offer fully automated tuning or tailoring of algorithm configuration and implementation, six vendors noted that they provide automated routines and/or graphical user interfaces (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.

In addition to user-facing GUIs (present in all offerings), all but two of the 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.

Technical Capabilities

As seen in Figure 2, 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, air handling unit (AHU) and variable air volume (VAV), fan coil units (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. Several vendors reported that they cover additional systems such as energy recovery ventilators (ERVs), other terminal units besides VAV boxes, solar panels, variable refrigerant flow (VRF) systems, BAS controls, and cogeneration.

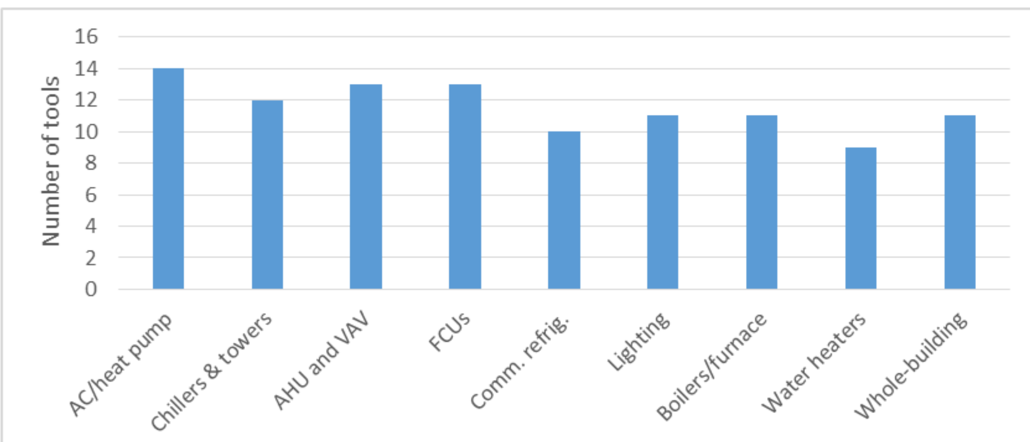

Figure 2. Systems covered in surveyed AFDD offerings

Nearly all of the tool vendors surveyed are able to detect faults in the majority of the fault categories in the survey: sensor errors, energy consumption, economizers and ventilation, 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 capable of determining at least some types of faults for whatever data can be provided, reflected in Figure 3.

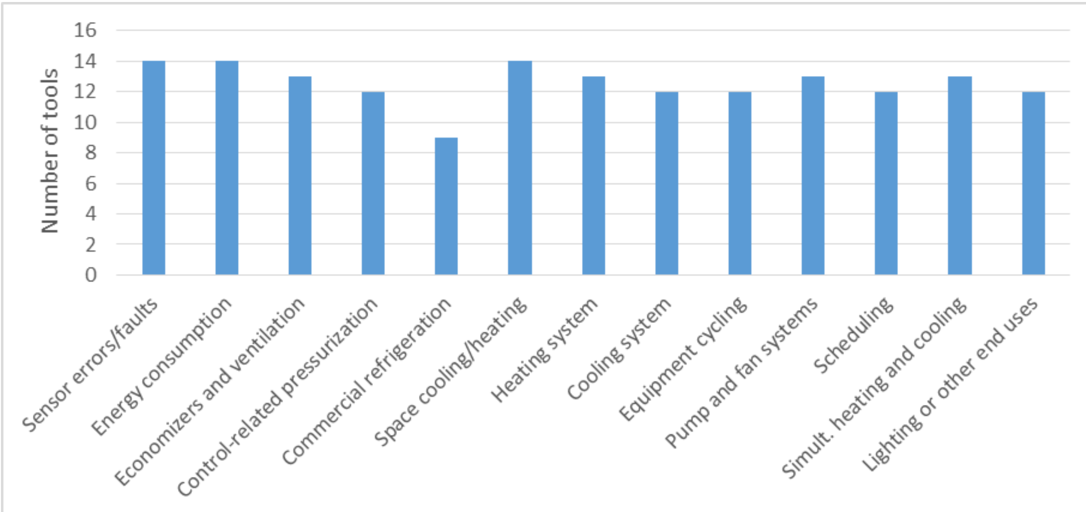

Figure 3. Categories of detectable faults in surveyed AFDD offerings

Most of the tools (12 out of 14) use rule-based algorithms, the majority of which apply some combination of expert systems, first principles, 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 4 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.

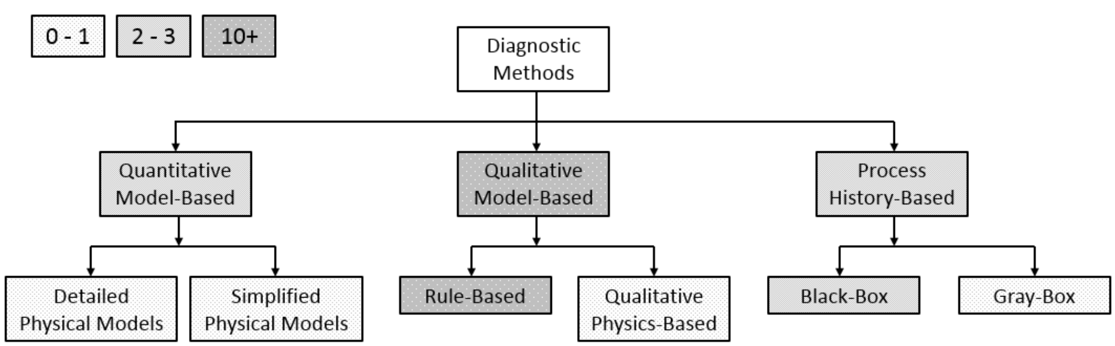

Figure 4. Methods and algorithms in surveyed AFDD offerings

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.

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 5. Other very common features were equipment degradation, conversion of energy impacts to cost impacts, key performance indicator (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 (e.g., cost of pending equipment failure), 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 but are important complements to the AFDD capabilities.

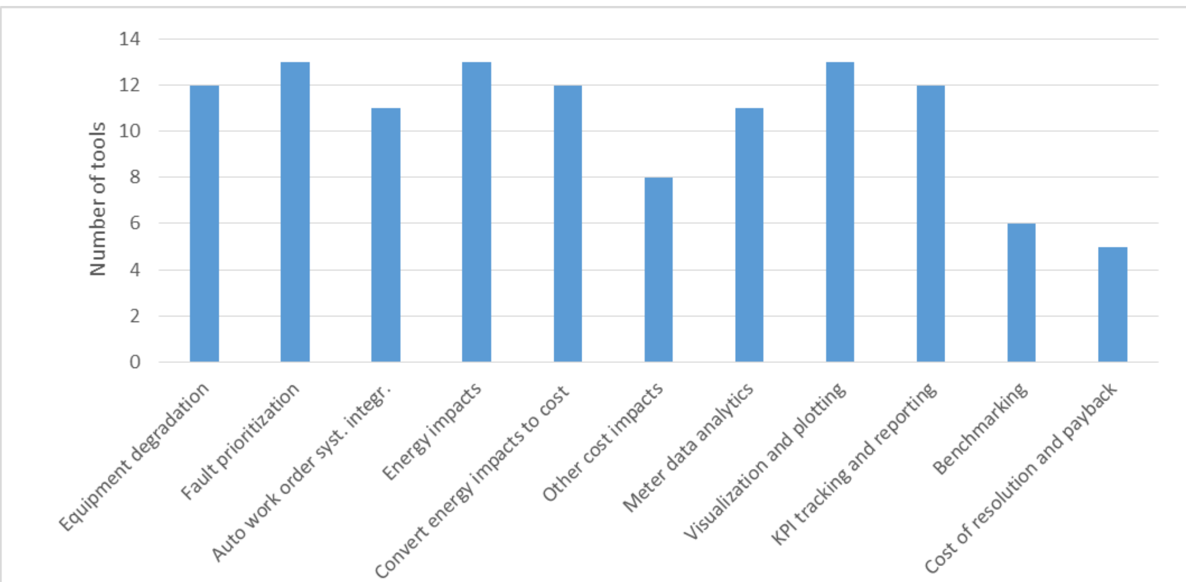

Figure 5. Relative frequency of a selected set of additional features of AFDD tools

Market Status and Barriers Summary

The assessment presented in this paper 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, however smaller facilities are less commonly served. 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. A further compelling evolution in the industry is the expansion of market delivery of AFDD through third-party service providers. Illustrated in Figure 6, 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, as well as the analysis-as-a-service provided by the AFDD vendor. This expansion offers the potential to increase access to the technology benefits for a new class of owners who otherwise may not be using it. However, the cost of third party services may vary significantly and each cost component should be defined in full to be able to compare across delivery options.

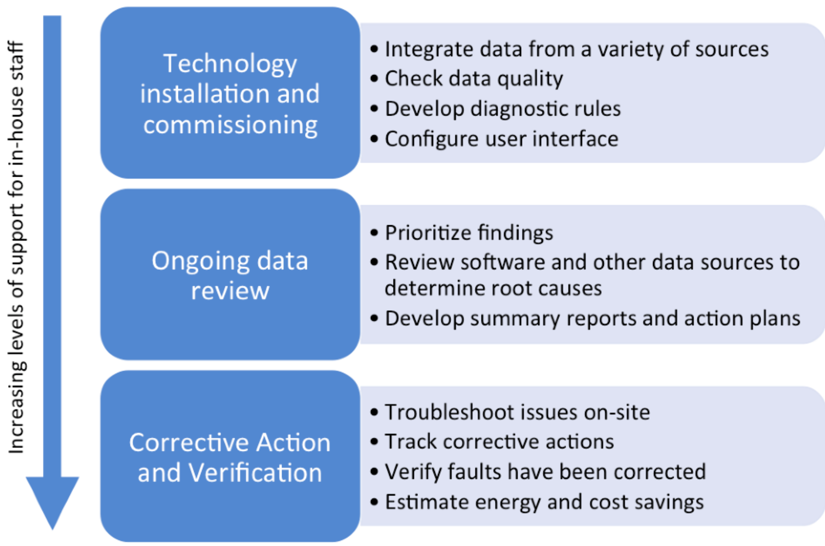

Figure 6. A spectrum of analytics-focused activities that service providers may offer their customers

While rule-based methodologies are still the norm, vendors are beginning to use process history-based techniques. Independent of the AFDD 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; while this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors between AFDD offerings 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 a 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 (diagnostics) 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."

AFDD 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 Kramer et al. 2017 for a snapshot of 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:

- Prospective users remain challenged in interpreting the value proposition of AFDD 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? How do I navigate this developing market with numerous evolving players and product options?
- Prospective users also face more specific implementation questions such as: What is the distinction between AFDD and BAS alarms? 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 contractors and service providers with in-house activities?

Organizational:

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

Technical:

- While improving, IT and data integration represent one of the largest barriers to scale. It is complex, expensive and crosses organizational business units; communications infrastructures are not easily leveraged for installation of analytics technologies.
- 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.
- 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.

Conclusions and 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. Some of these are technical development challenges, and some are 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. 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. Truly pervasive “plug-and-play” functionality is still being developed, as are solutions to automatically extract and interpret data across diverse systems. The ability to interface AFDD tools with computerized maintenance management systems (CMMS) is just beginning to be explored, and will streamline 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, AFDD, 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 building lifecycle.

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