Provider and User Perspectives on Automated Fault Detection and Diagnostic Products for Packaged Rooftop Units

Grant Wheeler,[1] Michael Deru,[1] Adam Hirsch,[2] and Kim Trenbath[1]

1 National Renewable Energy Laboratory
2 Torque Interactive Media

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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List of Acronyms

AFDD	automated fault detection and diagnostics
BAS	building automation system
FDD	fault detection and diagnostics
HVAC	heating, ventilating, and air conditioning
O&M	operations and maintenance
RTU	rooftop unit

Executive Summary

Automated fault detection and diagnostics (AFDD) is a tool that can help maintain the operation of heating, ventilating, and air-conditioning equipment at expected efficiencies, customize maintenance schedules, and alert building owners when occupant comfort is at risk of being compromised due to catastrophic failure. Industry experts have suggested that AFDD would be an ideal fit for commercial rooftop units (RTUs), given their large share of the commercial marketplace and high prevalence of faults. The value proposition and potential for RTU AFDD has been demonstrated sufficiently to be written in standards and codes. Title 24, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, and International Energy Conservation Code requirements have all included AFDD within the last few years. However, implementation of RTU AFDD has just begun in commercial buildings.

The goal of this project was to understand, based on the primary reporting of AFDD providers and building owners, 1) the features available for RTU AFDD in the market today, 2) how RTU AFDD is used by building owners and managers, 3) how well RTU AFDD meets their needs, and 4) what barriers stand in the way of its broad industry adoption. To achieve this goal, 13 AFDD providers were asked about their products and seven building owners were questioned about their practical experience related to the automated detection, diagnosis, and communication of RTU faults.

Automated Fault Detection and Diagnostics Product Providers—Main Findings

Although some AFDD providers' products were designed to detect a wide variety of RTU faults, several focused exclusively on economizer faults. This emphasis likely resulted from the recent inclusion of economizer fault detection in standards and codes, in particular California's Title 24, pointing to a direct impact of standards and code implementation on the RTU market. RTU size also appears to impact implementation of AFDD, with products mainly intended for larger RTUs, with capacity of 10 tons or more. The sophistication of diagnosis capabilities varied significantly among products, allowing us to develop a new classification scheme to differentiate them. Finally, communication of faults was most often provided via a website or app, and less frequently by email or other means; in particular, integration with work order systems is a desirable capability for building owners that requires custom integration for each provider due to the unique work order systems for each building owner.

Building Owners—Main Findings

Most building owners we communicated with managed large portfolios of building across different climates. They all experimented with AFDD by pilot testing a few buildings before rolling it out to the rest of the portfolio. Almost all of them developed customized AFDD solutions, whether in collaboration with a third party or completely in-house. The highest priority faults for the owners to detect related to zone cooling and heating; communication of faults was often done via a combination of email and a work order system. Integration of AFDD with a work order system was often labor intensive due to lack of standardization across work order software products. When asked about what additional AFDD features would be most beneficial, all building owners wanted some form of fault prioritization or filtering of faults to manage the large number of faults that initially accompany AFDD implementation. Although several AFDD products offer this capability, building owners often went with in-house solutions indicating other factors such as integration with work order systems influenced the decision to choose an AFDD provider.

Classification of Automated Fault Detection and Diagnostics Capability Levels
Based on the responses from both AFDD providers and building owners, it was possible to classify AFDD products according to their differing capabilities. This analysis suggested that more sophisticated AFDD capabilities, while available in the marketplace, are currently underutilized by building owners for RTUs. Most building owners initially acquired AFDD to meet relatively basic needs; while they are interested in eventually adding more advanced features with additional capabilities, they only want to do so after implementing more basic functions and managing the initially large number of AFDD-identified faults.

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1 Introduction

Fault detection and diagnostics (FDD) is the process of identifying anomalous behavior in physical systems and attempting to track that behavior to underlying equipment or control problems. FDD can be a manual, semiautomated, or fully automated process. Automated fault detection and diagnostics (AFDD) continuously and autonomously monitors the performance of systems, identifies faults, attempts to diagnose their causes, and communicates information about the faults and/or diagnoses to stakeholders in a position to take action to remedy them. This technology has the potential to: 1) streamline and improve maintenance operations, 2) support effective and energy-efficient system performance, and 3) extend equipment life. AFDD technologies have been applied to a variety of systems, with most applications in the transportation and industrial sectors because of the standardization of systems and high-value streams available. This report focuses on the application of AFDD to packaged heating, ventilating, and air conditioning (HVAC) units for commercial buildings, generally known as "rooftop units" (or RTUs) due to their typical location.

RTUs are the most common type of HVAC system in the commercial building market in the United States (EIA 2012); furthermore, they often operate with one or more faults due to poor maintenance, degradation, and improper control (Katipamula and Brambley 2005). For the purposes of this report, a fault is an equipment or control problem that causes key system operating parameters (e.g., space conditions such as temperature, humidity, air quality, noise level, etc., but also including other variables of interest such as power consumption) to depart from acceptable or expected values. A study of RTUs across the Pacific Northwest found that 91% of RTUs surveyed had one or more faults (Cowan 2004). This result illustrates the significant potential for applying AFDD specifically to RTUs. FDD and AFDD technologies have been applied to rooftop air-conditioning units for several years with various levels of sophistication and success (Katipamula and Brambley 2005; Heinemeier 2012). The California Energy Commission became the first regulatory agency to require AFDD for packaged HVAC systems of more than 4.5 tons by specifying AFDD for RTU economizer faults in Title 24-2014 (CEC 2016). International Energy Conservation Code 2015 and American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 90.1-2016 adopted similar requirements for air-cooled air conditioners of more than 4.5 tons with economizers, including but not limited to RTUs (IECC 2015; ASHRAE 2016). However, despite incorporation of AFDD for RTUs in well-known energy codes and standards, mainstream adoption of AFDD for RTUs has yet to become widespread.

This report documents the capabilities of RTU AFDD systems currently offered by manufacturers and how RTU AFDD is being used today by building owners and managers, based on primary data collected from industry representatives. Results include insights into how AFDD technologies for RTUs are being used in the field by building owners, the value that these systems provide, ideas on how they could be improved, and the challenges the users must overcome. The paper also:

- Proposes a classification system for RTU AFDD capabilities
- Provides RTU AFDD use cases
- Highlights specific research needs as identified by market players.

2 Background

2.1 Definition and Categorization of Automated Fault Detection and Diagnostics

According to Katipamula and Brambley (2005), the goal of FDD is "early detection of faults and diagnosis of their causes, enabling correction of the faults before additional damage to the system or loss of service occurs." This goal can be achieved in an automated manner (using AFDD) through four distinct processes (Katipamula and Brambley 2005):

- Continuous monitoring of system operations
- Using FDD to detect and diagnose abnormal conditions and associated faults
- Evaluating the significance of the detected faults
- Deciding how to respond.

Thus, the basic functionality of all AFDD products can be summarized as including monitoring, fault detection, diagnosis, and communication. Each feature is described in more detail below, including how this study treated each aspect.

Monitoring. The *continuous* nature of RTU monitoring by AFDD is an important distinction. Many FDD tools are available in the market that can be set up temporarily to assist with maintenance; however, these tools leave with the technician. For the purposes of this report, AFDD products had to be *permanently* installed to be included.

Fault detection. HVAC faults can be categorized in many ways. In one example, Heinemeier (2012) used three categories according to the types of sensors installed to collect data for the FDD: air-side, refrigeration cycle, and power. For this project, seven categories of faults were used to differentiate the various AFDD products, representing a subset of a broader list presented in Granderson et al. (2017): economizer, air-side, refrigerant, power, sensors, schedule, and zone cooling/heating. These fault-based categories were chosen rather than sensor-based categories because some AFDD providers have found unique ways to detect faults that may not correlate directly with a particular sensor.

Diagnosis. Katipamula and Brambley (2005) provided a framework for categorizing diagnosis methods that is widely accepted by building scientists. They separated diagnosis into three categories: quantitative model-based, qualitative model-based, and process history-based. In this project, respondents indicated that they used rule-based diagnostics when taking a qualitative model-based approach. Therefore, we used Katipamula and Brambley's original framework, but replaced "qualitative model-based" with "rule-based." These three diagnostic approaches are described in more detail below:

- **Quantitative model-based**. Model based on detailed physics that relies heavily on sensor inputs to determine abnormal behavior.

- **Rule-based**. Model based on physics or rules that relies on expert experience, namely thresholds between normal and abnormal operations. Although intuitive at first, these rules risk becoming complex, especially when considering simultaneous faults. Attention must be paid to keeping AFDD rules understandable by HVAC technicians and building managers.

- **Process history-based**. Uses historical data from the RTU to provide baseline performance, with abnormal operation determined by comparing to baseline performance.

A "mixed" diagnosis category was added because many AFDD products implemented more than one type of diagnostic method.

Further information was provided by identifying the location where the diagnostics were physically occurring. Granderson et al. (2017) provided four different logic locations for RTU AFDD: on the retrofit control itself (distributed), building automation system (BAS), cloud-based, and embedded (i.e., in the original RTU controller). A fifth "multiple" category was also included to account for situations where processing was done in more than one location. This survey made the distinction by asking specifically where the diagnostics occurred; this was a subtle difference from other surveys, which asked for the location of the AFDD *product*. In the survey, many companies provided a basic diagnostics capability locally, with additional diagnostics hosted on the cloud. This accounts for the need for a "multiple" category for AFDD diagnostics, which was not typically seen in other surveys. Building owners also often needed a multiple category because they combined BAS-based AFDD with diagnostics embedded in the RTU by the manufacturer.

Communication. For this final AFDD component, different ways to alert users to faults were highlighted by the survey, including website/app, email, text, local (at the RTU itself), and "other." The "other" case was most often a custom form of communication such as through a work order system.

2.2 Automated Fault Detection and Diagnostics Capability Definition

One of the market barriers to broader use of AFDD technologies for RTUs is the lack of a common framework for defining and discussing these technologies. Granderson et al. (2017) proposed such a framework; however, its use requires detailed knowledge of AFDD systems and lengthy lists of attributes, making it difficult for general industry practitioners (the audience for this report), as opposed to AFDD experts, to use. For the purpose of this study, a complementary AFDD classification scheme was used based on how advanced a product's diagnostic capabilities are; the goal of this approach was to help interested users understand what to expect from a given product and to quickly and efficiently compare multiple offerings.

Table 1 defines the four "levels" of the proposed AFDD categorization scheme, distinguished by their increasing analytical sophistication and ability to respond to detected faults.

Table 1. Levels of Diagnostic Capabilities for Rooftop Unit Automated Fault Detection and Diagnostics

Level	Features
1	• Continuously monitor with a frequency of no less than daily • Detect improper equipment or sensor behavior • Analyze and characterize/categorize faults • Communicate faults to the user
2	Level 1 plus the following items: • Prioritize faults based on potential loss of service and urgency of repair based on rules or experience • Validate sensor measurement accuracy • Store historical data • Provide external communication of faults
3	Level 2 plus the following items: • Provide broader information about faults, in terms of estimated impact on performance, energy costs, and expected repair costs
4	Level 3 plus the following items: • Adjust RTU controls to reduce fault impact until maintenance occurs • Calculate and store capacity and efficiency performance data in order to quantify the impact of faults on equipment performance • Prioritize faults based on calculated cost impacts and interruption of service • Initiate an automated fault-detection mode to test AFDD features

In summary:

- Level 1 AFDD systems provide basic capabilities for detecting faults and communicating them, but not necessarily determining the nature of the problem.

- Level 2 AFDD systems communicate information externally about the type of fault and its severity, in terms of its impact on building operations. Level 2 systems can also check whether sensors are working properly.

- Level 3 AFDD systems can estimate the impact of an RTU fault. This augmented ability can provide more information to the user about a fault's expected energy costs.

- Level 4 AFDD systems can estimate the impact of a fault on RTU capacity, efficiency, and energy consumption. This augmented ability can provide more information to the user and maintenance program about a fault's expected energy costs and suggestions for fixing the fault.

3 Approach

First, the National Renewable Energy Laboratory developed a list of AFDD providers and building owners applying AFDD to their RTUs, aiming to include a diverse set of industry stakeholders. In the end, the building owners were predominantly from the retail sector, the market that has seen the most active adoption of AFDD for RTUs. Owners of different building types should be approached in the future as they begin to leverage AFDD for their RTUs.

A standard invitation was sent to the list of potential interviewees, and a time was arranged for a 1-hour conversation. Interview templates were created to collect information about the following topics (see Appendix A for the full list of information requested from each group):

Requested Information from Automated Fault Detection and Diagnostics Providers

- Typical size of RTUs featuring their product
- Where their product has been sold
- Building types where the AFDD product has been installed
- Capabilities of AFDD product
- Experience with RTU market
- Market barriers to RTU market
- Suggested research.

Information Requested from Portfolio Building Owners

- RTU description
- Building details
- AFDD characteristics
- Summary of experience using AFDD
    - Faults found because of the AFDD product
    - Types of information provided by the AFDD product and frequency of reporting
    - Actions taken based on fault notifications.
- Change in maintenance schedule due to AFDD
- Market barriers to using AFDD products
- Suggested research.

The use of a template prompted standardization and easy analysis of the responses. In general, interviewee responses were kept anonymous by only presenting aggregated results; however, several individual responses were selected to highlight specific points, and included in the Results section. The data analysis was very simple, generally involving calculation of what percentage of responses fell into different categories.

4 Results

The aggregated results of the seven building owner interviews and thirteen AFDD product providers are presented below for each type of respondent separately where appropriate and then together when both groups were asked the same question, to allow comparison of their responses. A final section details how the relevant AFDD products execute the four FDD processes and the sophistication of their diagnostics, according to the capability level framework defined in the Background section. Appendix B includes a table containing a high-level overview of the features of the AFDD products corresponding to the interviewed providers. Most building owners interviewed were in the retail sector, as mentioned above, and owned large portfolios of buildings rather than a single building. Other building types represented included health care, recreation, and "other" (one interviewee was a broker for a commercial real estate company covering multiple building types), providing some diversity. The AFDD providers included a mix of large established companies and smaller companies that only recently entered the market for HVAC controls. Two of the AFDD providers were also RTU manufacturers; the remainder were focused on retrofit applications.

4.1 Automated Fault Detection and Diagnostics Providers

Geographical Activity

In order to identify geographical "hot spots" in the RTU AFDD market, interviewees were asked which states their products are sold in. The results, shown as the fraction of the 13 AFDD products sold in each state, are displayed in Figure 1. California had the most activity, followed by Illinois (Chicago specifically), Texas, and New York. Note that Figure 1 reflects the activity of the limited group of companies interviewed for this study; it does not preclude the existence of AFDD hot spots in other states. Several AFDD manufacturers could not specify exactly where their products are sold because they are factory installed in RTUs whose sales location are not tracked by the AFDD companies.

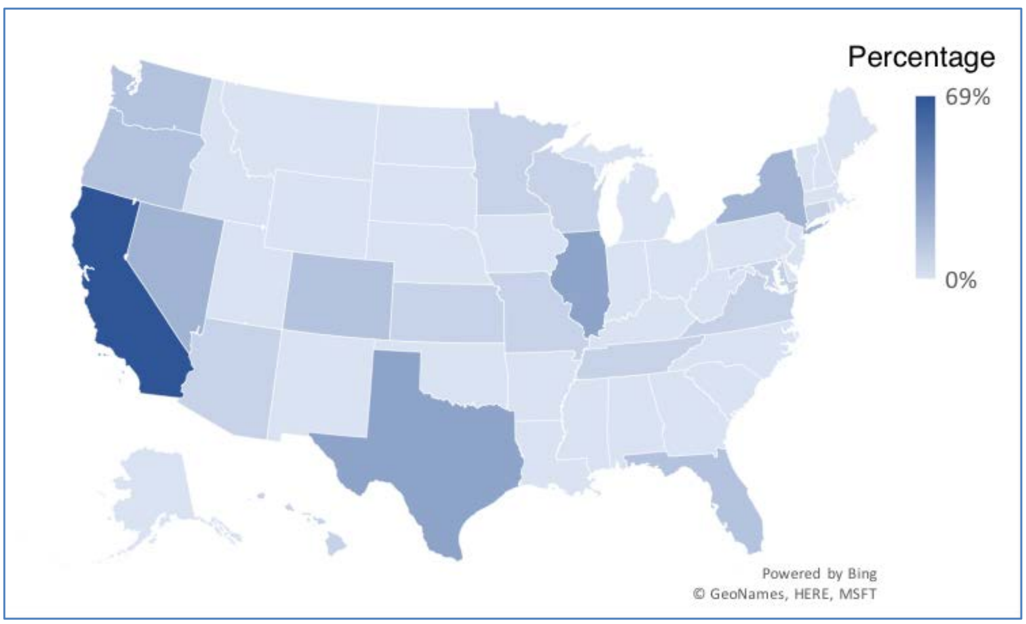

Figure 1. Rooftop unit automated fault detection and diagnostics provider activity by state

Title 24 Certification
Mandatory AFDD requirements for RTUs took effect in 2014, including the ability to detect and communicate the following RTU faults:

- Air temperature sensor failure/fault
- Not economizing when it should
- Economizing when it should not
- Damper not modulating
- Excess outdoor air.

Laboratory certification is required for compliance, as is in-field performance verification of AFDD capabilities for new RTUs. Sixty percent of the AFDD providers who responded to this question (7/11) stated that their products were certified as compliant with Title 24, the California Energy Code.

Rooftop Unit Capacity
Most of the AFDD products included in this study are applied to RTUs featuring a cooling capacity of 10 tons or more, generally termed "large" RTUs. Additionally, the market percentage decreases rapidly with decreasing capacity (Figure 2), indicating that the RTU AFDD market is heavily weighted toward higher-capacity RTUs. The very small percentage of solutions for 1–4 ton RTUs could result in part from the minimum size requirement for the Title 24 regulations.

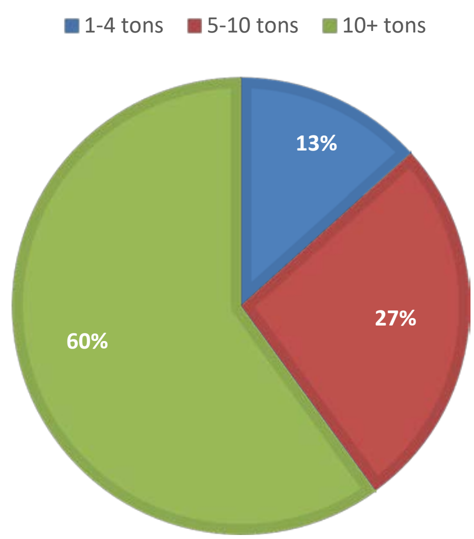

Figure 2. Fraction of automated fault detection and diagnostics products serving rooftop units as a function of cooling capacity (tons)

Additional Sensors Required for Fault Detection
Sensor installation can be a significant contributor to the total cost of an AFDD system. Although it may be appealing to add multiple sensors to improve the effectiveness of AFDD algorithms, the AFDD manufacturer must strike a balance between the benefit these sensors deliver and their additional cost. One strategy to address this challenge is to—as much as

possible—leverage the sensor data already typically collected from RTUs and stored by a building's BAS.

AFDD manufacturers were asked to specify the minimum number of additional sensors (beyond those typically installed by RTU manufacturers) they required as inputs for their fault detection algorithms. Figure 3 shows the results, in terms of the fraction of respondents in each category. The majority of AFDD manufacturers interviewed wanted 6–10 sensors installed with their product. At the opposite end of the spectrum, one company required no additional sensors, relying instead on available sensor data from the RTU or BAS to detect faults.

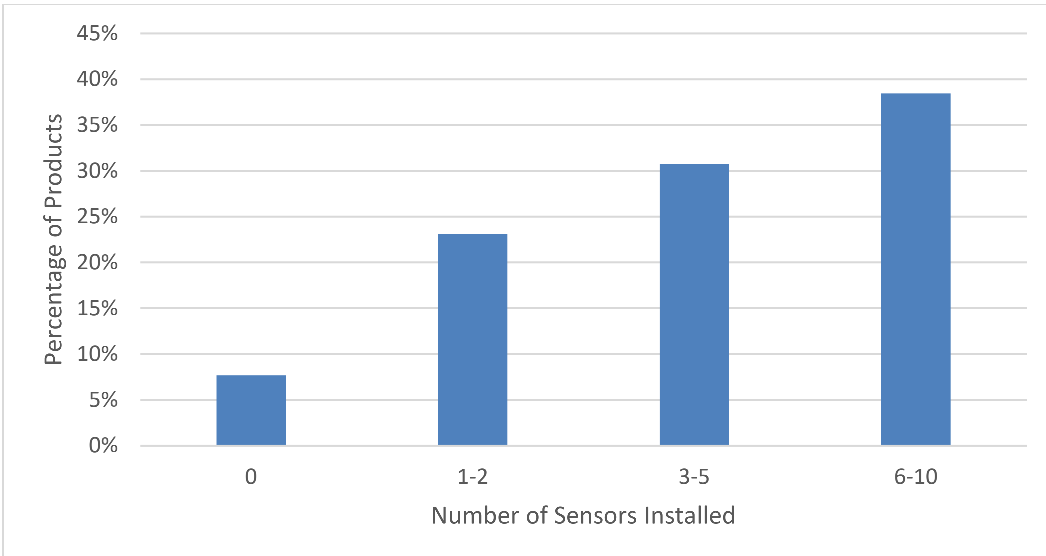

Figure 3. Number of sensors installed with rooftop unit automated fault detection and diagnostics systems

The most common sensors installed by AFDD companies were for measuring the air temperature of various airflows and amperage of electrical components. RTU supply, return, and outdoor temperatures appear to be common temperature measurements. Amperage was often measured as a proxy for power and some companies measured the current of only one phase of the power system rather than all three (most RTUs are powered via 3-phase 480 VAC). Other companies measured amperage and voltage to more accurately calculate power.

Fault Occurrence
Table 2 describes the most prominent faults that occur in RTUs in each fault category, according to the reporting of the AFDD providers.

Table 2. Common Faults Encountered in Rooftop Units

Fault Category	RTU Fault
Zone cooling/heating	• Cooling- or heating-stage failures • Excessive cycling
Schedule	Operating outside of scheduled hours
Refrigerant	Refrigerant management issues including low or high charge
Air-side	Supply air temperature issues
Economizer	Stuck outdoor air dampers
Refrigerant or power	Failed condenser motor

Areas for Improvement According to Automated Fault Detection and Diagnostics Providers

Table 3 summarizes future directions for research and development efforts needed to improve AFDD products, according to their providers.

Table 3. Actions Identified by Providers to Improve Automated Fault Detection and Diagnostics

Category	Research Needed
Validation	• Develop pilot testing programs to quantify the economic costs and benefits of AFDD to clearly define the value proposition of AFDD • Evaluate the accuracy of fault detection and diagnostics algorithms using laboratory and field measurements
Utility Engagement	• Create programs to incentivize uptake of AFDD • Increase utility awareness of AFDD
Market Outreach	• Increase building owners' awareness of the economic costs and benefits of AFDD and their understanding of different AFDD capability levels • Develop best practices for installation, logistics, customer service, and full integration with typical operations and maintenance (O&M) processes to support adoption and effectiveness of AFDD • Educate building managers and HVAC technicians so they see AFDD as a valuable tool to be integrated into their daily routine rather than as an annoyance to be circumvented • Have RTU original equipment manufacturers send data to servers, giving building owners motivation to buy AFDD for smaller RTUs (life cycle cost) • Develop regulations for accurate measurement of performance • Interview stakeholders before and after installing AFDD about how fault detection is working in the field; for example, how effective is AFDD at motivating action to repair faults?
Product Development	• Create additional rule-based detection algorithms • Energy savings analysis of sophisticated AFDD capabilities when connected to the internet versus more limited stand-alone capabilities when not connected • Work with RTU manufacturers to send sensor data to online servers to avoid the expense of installing additional sensors. Alternatively, make embedded sensor data on the RTU's controller available to retrofit controllers through open protocols (BACnet, Modbus).

4.2 Building Owners

Deployment Strategy

The majority of building owners used customized products, as shown in Figure 4. Some 71% of the building owners chose to work with a commercial AFDD manufacturer, whereas 29% decided to create their own AFDD product in-house. Only one building owner went with an "off-the-shelf" AFDD product. This indicates that current AFDD products may not match the needs of portfolio building owners to the degree that they choose to significantly customize existing products or even develop their own AFDD products from scratch.

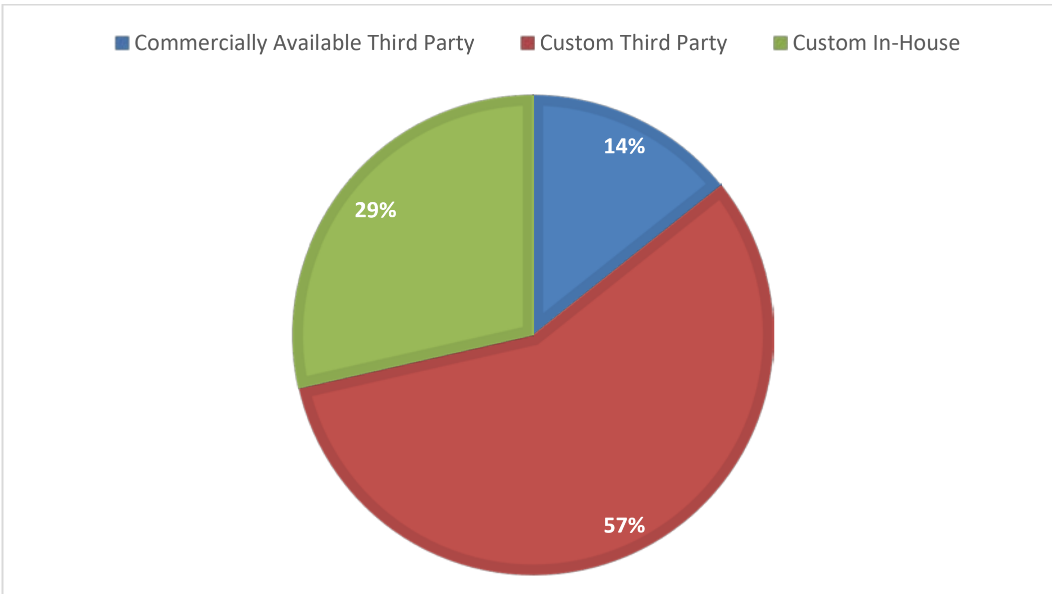

Figure 4. Type of automated fault detection and diagnostics system for building owners (seven total)

As mentioned previously, all the building owners interviewed had large nationwide building portfolios. Due to their large portfolios, most tested AFDD products via a pilot on a small subset of buildings. This strategy was used for two reasons: to prove the utility of AFDD and to reduce the risk of AFDD installation. It is also very difficult to quickly install AFDD across an entire building portfolio. As an extreme example, one building owner said it took almost 10 years to completely retrofit all buildings, thus highlighting why pilots are a logical starting point to validate a new technology.

Faults Detected

Table 4 summarizes the degree to which different faults were detected across multiple companies by AFDD. Economizer issues appeared to be the fault encountered by the most companies.

Table 4. Most Common Faults from Building Owners

Fault Categories	Most Common Faults
Economizer	• Dampers • Defective economizer
Sensor	• Sensor off-line
Zone cooling/heating	• Low-/high-temperature alarm

Interestingly, building owners highlighted sensor faults, which were not mentioned by the AFDD providers; at the same time, the building owners did not report refrigerant, power, or schedule faults that did make it into the provider list. The two groups do overlap regarding economizer faults and zone cooling/heating faults. In the case of schedule faults (e.g., Fan ON versus AUTO or set point versus setback scheduling), it is possible that for this group of building owners they occurred but were picked up by their buildings' BAS systems rather than by AFDD. For smaller buildings or individual buildings without BAS, schedule faults could be an important AFDD feature.

Early Challenges following Implementation

Many building owners mentioned that they were initially swamped by faults following AFDD implementation. As a result, short-term energy cost savings from improved controls and equipment performance may initially be overwhelmed by a significant increase in the labor costs of fixing a large backlog of previously undetected RTU faults.

Every building owner cited the need to implement prioritization and/or filtering systems to manage the large influx of faults detected by their AFDD systems. The initial deluge of faults has also led owners to focus on relatively simple AFDD functionality. Most building owners planned to add more advanced capabilities to their AFDD product but have deferred those plans until after they have installed more basic AFDD on the entire platform and are able to handle the initial surge of resulting work orders.

Integrating Automated Fault Detection and Diagnostics into Existing Maintenance Workflows

Another important question for building owners to answer is how AFDD will affect their maintenance procedures. As mentioned previously, upon first installing AFDD, all building owners saw an increase in work orders or maintenance calls. The majority eventually used AFDD to justify reducing preventative maintenance, and several experienced reduced emergency maintenance. All building owners used the data and diagnoses from AFDD to assist technicians with both preventative and emergency maintenance. This additional value of AFDD could improve its economic return on investment; quantifying this potential benefit is an important subject of future research.

Areas for Improvement of Automated Fault Detection and Diagnostics according to Building Owners

Building owners were also asked about what is needed to improve RTU AFDD. Owners made the following requests for additional research and development:

- Determine the impact of failure
- Prioritize alarms
- Send faults to service provider
- Diagnose condenser fan faults
- Tell us which units to replace
- Keep data for at least 3 years
- Develop products that can work with new and old equipment
- Provide access to RTU manufacturer sensor data
- Develop products that are not specific to RTU manufacturer
- Install AFDD without replacing assets
- Develop self-correcting AFDD that adjusts operation during a fault event as close to real time as possible, resulting in granular energy savings.

Building owners universally asked for a better way to describe the value proposition of AFDD. They also asked for additional guidance on better fault diagnosis and more robust AFDD. Furthermore, a common request was to create a process to implement AFDD across an entire portfolio of buildings.

4.3 Comparison of Responses to Technical Automated Fault Detection and Diagnostics Questions

AFDD manufacturers and building owners were asked the same questions about their experiences with the four processes that constitute AFDD: monitoring, fault detection, fault diagnosis, and communication. This section compares the aggregated responses of the two interview groups.

Faults Detected

Building owners and AFDD providers were both asked about the type of faults detected by their AFDD systems, according to the same seven categories. Their responses are shown in Figure 5 for comparison. The largest discrepancies were economizer and zone cooling/heating faults. The difference in economizer faults could largely be driven by regulations that push AFDD providers to detect economizer faults. Zone cooling/heating faults are the easiest to detect when comparing zone set point versus actual temperature. This most often requires information from the thermostat, which is difficult for AFDD providers to acquire, either because of the cost of installing a sensor inside or communication issues with legacy thermostats. In contrast, most building owners with BASs already have access to the thermostat signal. This result points to building owners leveraging their existing BAS systems for some basic AFDD functions.

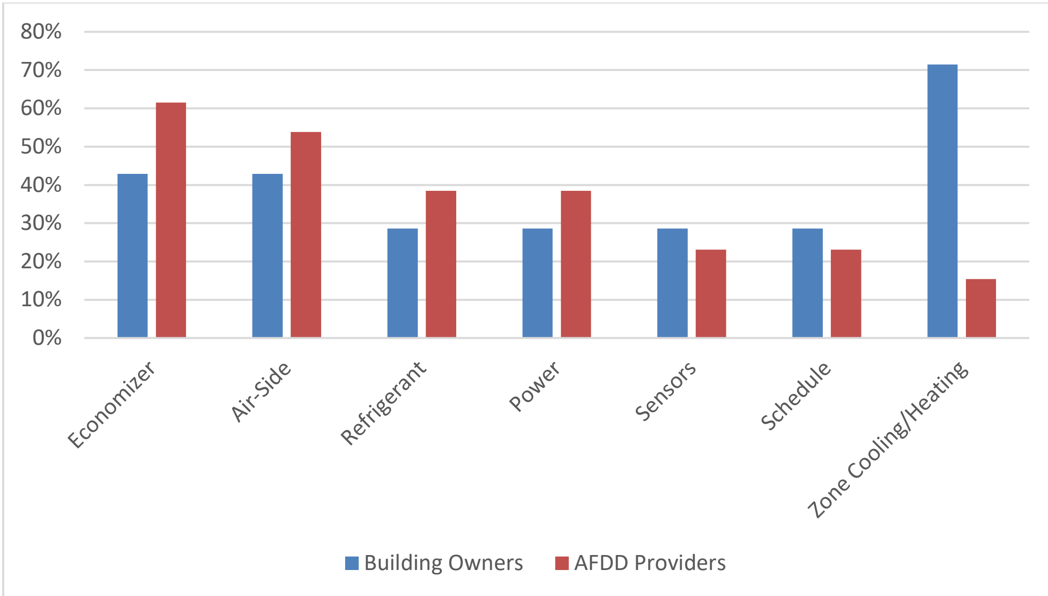

Figure 5. Type of faults detected

Automated Fault Detection and Diagnostics Deployment Strategies

Both groups were also asked about the location of the processors used to run the AFDD diagnosis algorithms. Figure 6 shows their answers. While many AFDD providers deliver diagnostics via a retrofit controller, cloud-based and multiple location strategies were just as common. Building owners predominantly used multiple solutions for diagnosis, often combining BAS and embedded (i.e., embedded in the RTU controller) diagnostics, but they never relied solely on retrofit controllers or embedded solutions.

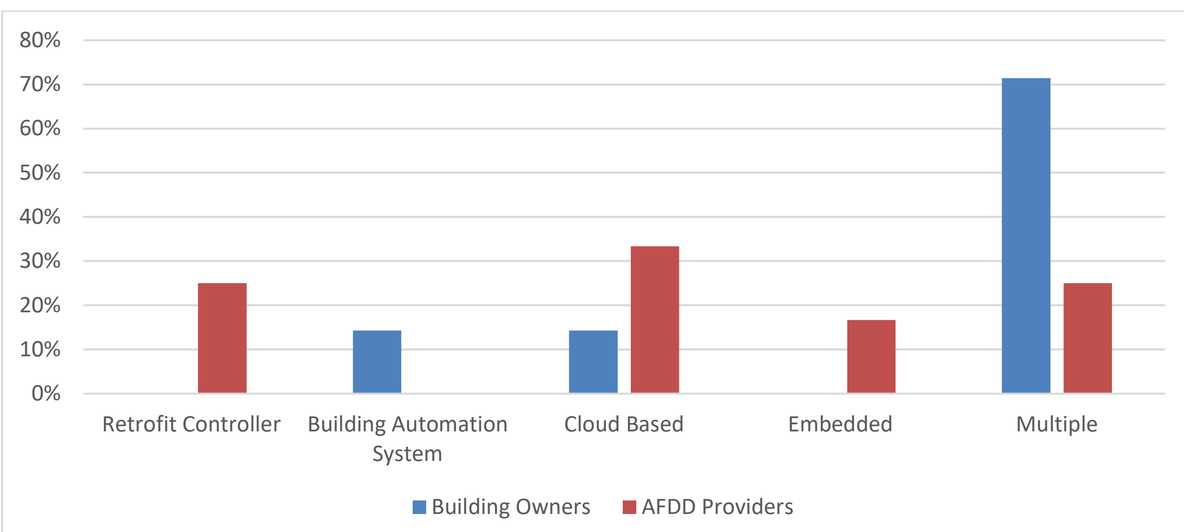

Figure 6. Location of automated fault detection and diagnostics system diagnosis

Diagnosis Methods

Both groups of interviewees were asked to define how they diagnose faults, based on the categories defined by Katipamula and Brambley (2005). Most owners (Figure 7) used rule-based or mixed methods. Only one interviewee used the more complicated model-based approach.

Several interviewees used a process history-based approach, but never as a stand-alone method. It is also worth noting that several of the building owners with only rule-based diagnostics wished to add process history-based diagnostic capabilities in the future. So, for the most part, building owners and AFDD providers used similar approaches in this area.

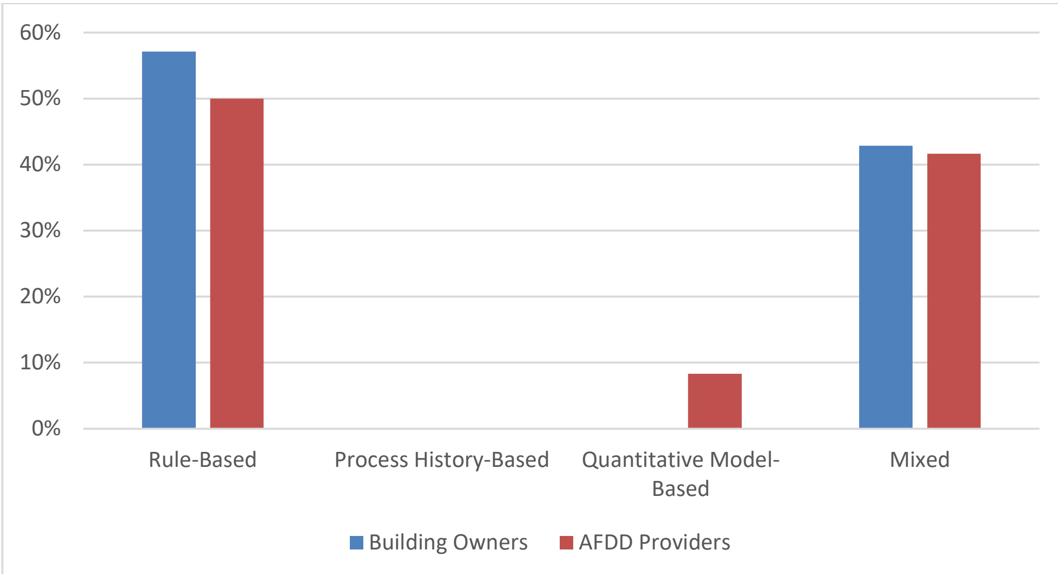

Figure 7. Automated fault detection and diagnostics diagnosis approaches

Communication Strategies

The final stage of AFDD is communication of the fault. We asked what types of communication were used, as shown in Figure 8. Building owners and AFDD manufacturers both used email to communicate faults. However, local (i.e., at the RTU) and text communication were less common with building owners. The largest discrepancy between building owners and AFDD manufacturers was on direct communication to work order systems, which was recorded in the "other" category. Although several AFDD manufacturers had the capability to communicate directly with a work order system, this was a custom capability. Most building owners connected their AFDD system to their work order system. Other forms of communication (such as email) were only for emergency cases. This highlights the difficulty of creating a standard AFDD product, because each company's work order system is likely to be unique to the company.

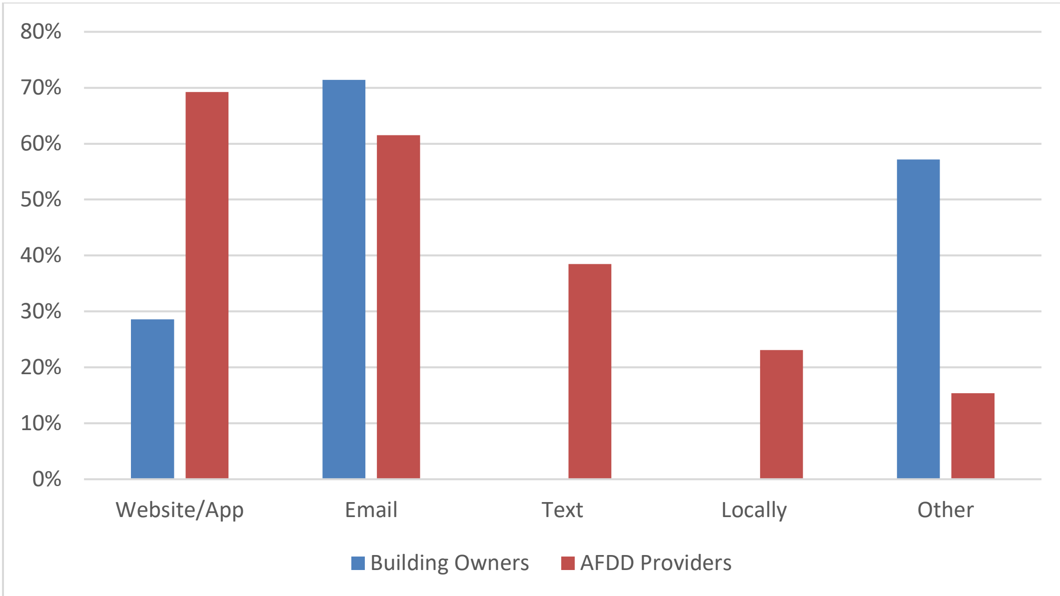

Figure 8. Forms of fault communication

4.4 Automated Fault Detection and Diagnostics Capability Levels

Each AFDD product was categorized based on the levels of capability described in Table 1. This was done to verify the description of each level of capability and to understand how current AFDD products for RTUs are distributed among the different capability levels. The level of each AFDD product was easily determined, and there were no gray areas, which suggests that the metrics and separations between levels were appropriately determined. Figure 9 illustrates the capability levels of the AFDD products sold by the AFDD manufacturers and used by building owners. The majority of products were determined to be at a level 1. Some AFDD products were level 3; however, these products were rarely used for RTUs by the building owners interviewed for this study. None of the products researched met level 4 capability, which was defined based on discussions with the project participants. Therefore, it appears that the more advanced level of AFDD has not yet reached the RTU market.

Building owners are split evenly between level 1 and level 2 capability. Most owners required external communication of faults and some form of prioritization found in level 2 products, viewing this capability as more important than improved absolute accuracy and fidelity. The only distinction to move most building owners to a more advanced capability level (level 3) is providing the impact of a fault to RTU operation. Many building owners expressed interest in this next level of capability.

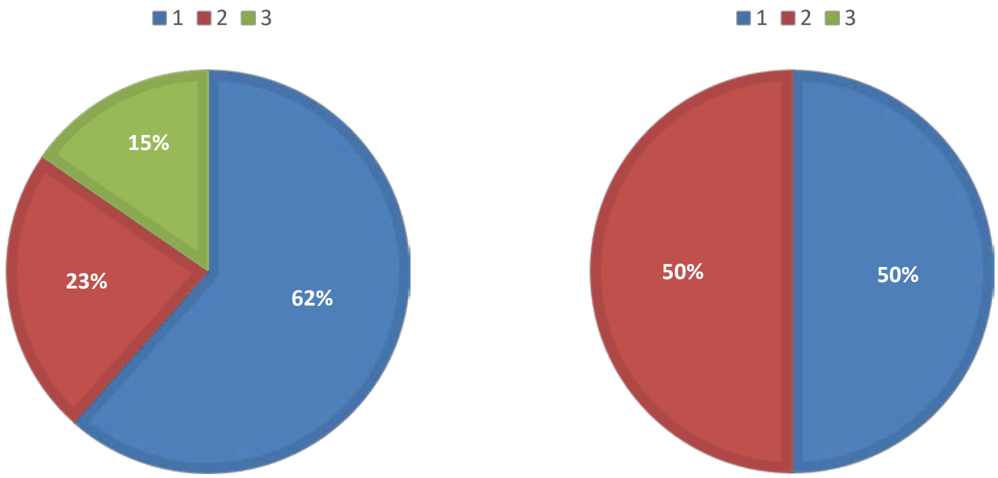

Figure 9. Capability level of automated fault detection and diagnostics systems for (left) providers and (right) building owners

5 Building Owner Portraits

Two of the interviewed building owners agreed to share the details of how they implemented AFDD for RTUs to provide a broader description of their experiences and lessons learned. Both added AFDD capabilities across their RTU portfolio but took very different approaches. One company, a health care provider, used a third-party provider to perform installation and programming of a commercially available solution while the other, a nationwide combined retail and grocery superstore owner, developed its AFDD system in-house.

5.1 Health Care Provider

The featured health care provider owns thousands of small commercial buildings across the United States. As a health care provider, it was unique in the interview group. It originally piloted many off-the-shelf AFDD products before settling on one that best met the company's needs. However, the selected product still required customization to enable communication with the company's new RTUs and integration with its work order system. When AFDD was first implemented, the company's experience was "…data overload. We received about 500 alarms per day. We had to figure out a way to find the important alarms."

The company formed a fault diagnostics team, which did some initial troubleshooting and assessed the urgency of repairing each fault. For emergency issues, the fault diagnostic team worked with internal technicians to solve the issue. It also acknowledged that the AFDD-generated work order requests initially increased to a point where it did not have the budget to fix all the faults. The company is still in the process of rolling out AFDD to all of its buildings and is considering adding more sensors. Next steps include looking at integrating AFDD with scheduled maintenance and proactive replacement.

This experience highlights the need to prioritize or filter faults. In addition, it may be reasonable to expect an increase in maintenance costs during the first year of AFDD implementation, with increased work orders offsetting potential savings as a backlog of previously undiscovered faults are addressed.

5.2 Big Box Superstore

This owner of more than 1,800 stores in the United States started implementing AFDD for RTUs in 2017. It created a customized AFDD product that monitors/collects RTU component shutdown “critical” faults through a BAS and sends them to a work order system. Enabling the AFDD initially exposed faults/alarms that were most likely present for months (maybe years). This translated to close to 25% of the fleet with qualifying faults and repairs. After the initial cleanup hump, however, the fault rate stabilized to closer to a 10%–15% fault rate.

Critical fault/alarms selected included only those that locked out major components, (i.e., motor overload, compressor high and low pressure, heat lockout). Mapping/selection of critical alarms was required for each different RTU manufacturer type because alarm/fault naming convention varies by manufacturer.

The company continually expands the number of RTUs within the AFDD pool through the addition of new RTUs. Implementing the AFDD program on older technology RTUs has been a challenge due to undetailed alarming/fault capability from the older manufactured units.

Through 2019, it has more than 12,000 RTUs capable of AFDD, although it only enables a percentage of them in order to balance/maintain financial goals. Overall, company representatives say that AFDD has created a more stable indoor environment for their stores without increasing long-term repair expenses. They have leveraged the data from this program to identify themes/trends in alarm/fault categories. During the second year of the program, the business has successfully reduced the alarm volume by modifying standard maintenance practices and control programming strategies.

This example illustrates the scale of the challenges encountered when implementing AFDD technology across a large portfolio. Like the health care provider, the big box superstore company also experienced a large influx of faults at first. It needed a customized AFDD product that was uniquely suited for its diversified fleet, allowing it to be implemented across the portfolio.

6 Recommendations

Comments from interviewees and analysis of the results produced two overarching recommendations from this study—first that standard categories be established to help compare the capability levels of AFDD products and second that methods in the literature developed to quantify the potential energy and cost savings of AFDD be transferred to the market. Several detailed frameworks have been proposed in the literature, but it appears that there is a need for an easily understood classification system focused specifically on the sophistication of a product’s diagnostic capabilities, as discussed in Section 2.2. The impact of AFDD has also been discussed at length in the literature, but it has not yet significantly driven uptake on AFDD products in the market. Awareness of AFDD can be increased through U.S. Department of Energy and national laboratory support, for example through the Advanced RTU Campaign (DOE 2019), and by providing utilities with reasons to promote AFDD specifically for RTUs.

There is still a lot of opportunity to research provider and user perspectives on AFDD for RTUs. Questions about prevalence, impact, and misdiagnosis of AFDD were ultimately not answered by the interviewees because they are still gathering the necessary experiences, knowledge, and data. However, there was great response when asked if data could be shared from building owners and AFDD providers with the National Renewable Energy Laboratory. Future work with field data may help identify the impact and prevalence of faults related to RTUs.

One of the most critical elements determining AFDD effectiveness today, rivaling the need for improving AFDD sophistication and accuracy, is how the customer integrates AFDD into their O&M procedures. Often, AFDD is implemented as a "bolt-on" to their normal process and therefore seen as a nuisance. By not creating an "O&M playbook" that fully integrated AFDD, they missed out on many of its benefits. Research into developing a standard O&M playbook of daily O&M procedures, which includes AFDD and that could be adapted for use by building owners to fit their particular circumstances, would be a valuable resource for the industry. This playbook would include a practical strategy to handle the inevitable initial surge of backlogged issues that accompanies AFDD adoption and to integrate the AFDD into their daily O&M procedures once the backlog is cleared. Reflecting the experience of the building owners in this study, it could also feature a tiered approach, starting with a basic and very practical AFDD system but also including straightforward future steps to enhance that system (e.g., adding prioritization of faults), ideally without having to add more hardware (i.e., sensors) at the site.

Regarding AFDD integration, there appears to be a broad demand for interoperability between AFDD products and work order systems used by companies to manage and automate their O&M processes. Research into communications between platforms to improve interoperability could bear fruit in a more streamlined plug-and-play system with decreased installation, setup, and reconfiguration costs.

In addition to developing an AFDD-friendly O&M playbook and improving interoperability, a research program to quantify AFDD-related savings in scheduled and emergency maintenance costs (reported anecdotally in this study) could provide much-needed empirical evidence of decreased costs to catalyze the uptake of AFDD. Such a program should include a diverse group of companies and compare their O&M costs in two regions, one with AFDD integrated into their processes and the second with business as usual.

7 Conclusions

The responses provided by the project participants give an overview of the nascent AFDD market for RTUs from the perspective of product providers and their customers, the building owners. Large portfolio owners were the only type of building owners interviewed for this study, and they often required custom AFDD products tailored to their buildings in contrast to the "off-the-shelf" products developed by the AFDD companies. This disconnect could be observed when considering building type, fault categories, and communication categories. However, further work is necessary to determine whether this disconnect was an artifact of the particular group of AFDD providers and building owners interviewed for this project or whether it reflected an actual market misalignment. It could be both; i.e., the large building portfolio owners included in the study all use BAS systems, which can influence which faults show up in the AFDD system, while off-the-shelf solutions generally require reconfiguration to meet specific owner needs. Cooperative research and development, such as that outlined in the recommendations section above, could help bring AFDD providers and customers into better alignment and streamline integration with existing O&M processes.

AFDD manufacturers appear to be designing their products to meet state regulations; specifically, Title 24 from California was noted as an important factor for AFDD design. The market also appears to be correlated to RTU capacity, with larger-capacity RTUs more likely to use AFDD. Further analysis highlighted the number of sensors installed, location of diagnosis, and type of diagnosis. Most diagnosis types are either rule-based or mixed. Most AFDD products need 6–10 sensors for full functionality. As a last step, each manufacturer's product was assigned a level of capability as defined in this document. Most products were level 2 of four levels, indicating that additional capability is possible. However, considering the difficulty of proving the value proposition, more capable AFDD products are unlikely to enter the RTU market in the near term.

All building owners interviewed began using AFDD through a pilot with a subset of buildings. Most building owners used custom AFDD products, whether developed by a third party or in-house. Most building owners connected their AFDD to a work order system to reduce needless extra communication and to streamline action to resolve faults. However, this integration often required extra work because AFDD products from the providers interviewed for this study are generally not designed to connect to work order systems out of the box. The owners universally experienced a large influx of faults at the beginning of the pilot, which required a great deal of effort to manage and filter. It is unclear why the filtering capabilities of level 2 products were either insufficient or not leveraged for this purpose. The majority of building owners reported that they subsequently experienced decreases in preventative maintenance and emergency maintenance, a result that needs to be substantiated with additional quantitative research. Lastly, most building owners included their building's BAS systems as part of "multiple" diagnosis location AFDD systems; by contrast, AFDD providers generally provided solutions that were independent of the BAS systems, limiting their access to data that is already routinely collected. Therefore, an area of future research is improved interoperability between AFDD systems and BASs.

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Appendix A. Questions Asked

Automated Fault Detection and Diagnostics Providers

- Building Characteristics
  - What types of buildings do you work with (select from CBECS list of commercial building types)?
  - What geographic regions have you sold your product in (select from list of U.S. states)?
- RTU Characteristics
  - How many RTUs are you currently providing AFDD to?
  - What size are the RTUs (select from: 1-4 tons, 5-10 tons, 10+ tons)?
  - What type RTUs are your products used with (low vs. high efficiency)?
  - Retrofit or new construction?
  - Do the RTUs offer any AFDD from the factory (and do you leverage this AFDD if yes)?
  - If OEM, do you offer an interface with your AFDD for others to use?
- AFDD Characteristics
  - What is your AFDD Product?
  - Where is your AFDD diagnostics located?
  - How do you detect faults?
  - How do you diagnose faults?
  - Do you detect simultaneous faults?
  - Can you alter RTU operation in response to a fault?
  - Is there any feedback from the fault?
  - Can customer feedback affect AFDD operation?
  - How long has your product been commercially available?
  - How many faults can the AFDD product diagnose with the standard/minimum number of sensors
  - What faults does your product detect (select all applicable from: Economizer, Refrigerant, Air-Side, Power, Sensors, Zone Cooling/Heating, and Schedule)?
  - Is your product Title 24 compliant?
  - What sensors are installed with the AFDD product?
  - How many sensors are needed for your product to work properly?
  - How are faults communicated to the user (select all applicable from: Local, Website, Text, Email, Other)?
  - Who is the fault communicated to?
  - What actions are taken after the fault is communicated?

- Are faults prioritized?
- Is automated filtering available for faults?
- Is the AFDD package standard or customizable?
- How does the company charge for the product (one-time cost or SaaS)?
- Does the AFDD product offer interfacing with Service providers?
- Does the AFDD company provide other useful services?

- AFDD Installation
  - Who installs the AFDD system?
  - Is an initial pilot typically performed (describe if yes)?
- Experiences with AFDD
  - Most common RTU faults encountered?
  - What faults have you found?
  - What percentage of RTUs have had faults initially?
  - What percentage of RTUs have developed faults after AFDD installation?
  - How many fault detections have been false alarms/misdiagnoses?
  - Have you found any faults that were missed by the AFDD product?
  - How do you handle non-critical AFDD detected faults?
  - How do you handle critical AFDD detected faults?
  - How do you decide which faults are critical?
  - What customer feedback have you received?
- AFDD Wish List
  - What more would you like from an AFDD product?
- Data Collection
  - Does your AFDD system collect data?
  - Do you have any data that you could provide to add any context to the questions above?

Building Owners

- AFDD Program
  - How do you "sell" an AFDD program internally in your company?
  - Did you perform a pilot with the AFDD product (if yes, describe it)?
- AFDD Characteristics
  - What AFDD product are you using?

- How many faults can it diagnose?
- Does it do any advanced root cause analysis or resetting?
- What faults does the AFDD product find (select all that apply: Economizer, Refrigerant, Air-Side, Power, Sensors, Zone Cooling/Heating, Schedule)
- Did you pick the AFDD product to be Title 24 compliant?
- What sensors were installed with the AFDD product?
- Location of diagnostics?
- Type of diagnostics?
- How are faults communicated (select all that apply: Local, Website, Text, Email, Other)?
- Who are the faults communicated to?
- What actions are taken after a fault is communicated to?
- Are any faults prioritized?
- Is the AFDD package standard or customized?
- How does the company charge (one-time cost or SaaS)?
- Does the AFDD product offer interfacing with service providers?
- Does the AFDD company provide other useful services?
- What is the most common fault detected?

- AFDD Installation
  - Who installed the AFDD system?
  - Did the AFDD system find faults from your current preventative and emergency maintenance schedules?
- Building Characteristics
  - What building type(s) do you own?
  - What is their average gross floor area?
  - What ASHRAE climate zones are they located in?
- RTU Characteristics
  - How many RTUs do you own?
  - What size are they?
  - What type of RTUs do you have (low vs. high efficiency)?
  - Do your RTUs offer any AFDD from the factory (if yes, do you use it?)?
- Current Maintenance
  - Who handles your preventative maintenance?
  - Who handles your emergency maintenance?
  - What is your current maintenance schedule?

- What faults do you look for?
- How do you handle emergency fixes?
- How are you currently informed about emergency faults?
- How are you currently informed about minor faults (those that do not prevent cooling/heating)?

- Experiences with AFDD
  - What is your most common fault?
  - What percentage of RTUs have had faults initially?
  - How many AFDD detections have been false alarms or misdiagnoses?
  - Have you found any faults that the AFDD product missed?
  - Other issues?
- Changes in Maintenance
  - How do you handle non-critical AFDD detected faults?
  - How do you handle critical AFDD detected faults?
  - How do you determine which faults are critical?
  - Has your PM schedule changed due to AFDD?
  - Has your EM schedule changed due to AFDD?
- AFDD Wish List
  - What more would you like from an AFDD product?
- Data Collection
  - Does your AFDD system collect performance data?
  - Do you have any data you could provide to add context to the questions above?

Appendix B. Commercially Available Rooftop Unit Automated Fault Detection and Diagnostics Systems

Appendix B provides a sample list of automated fault detection and diagnostics (AFDD) manufacturers and the faults that their products can detect. This list was compiled from a review of AFDD manufacturers' publicly provided information and may not cover all capabilities available for individual products. Cells with question marks (?) represent uncertainty in this feature availability. There are many more AFDD manufacturers that can be used for rooftop units (RTUs). This list is only meant to provide examples of available AFDD products.

		Lennox Prodigy	Carrier WeatherExpert	Trane Precedent, Reliatel, Intellipak	York Simplicity SE, Predator	Switch Automation	ClimaCheck ConCom	ECore	Ezenics AFDDI	Honeywell Jade	Pelican Wireless Pearl	Johnson Controls Simplicity SE	Virtjoule	XCSpec Economizer Pro	Transformative Wave eIQ
Faults	Economizer	*	*	*	*	*	*		*	*	*	*		*	*
	Refrigerant		*	*		*	*	*	*		*	*	*	*	
	Air-Side		*		*	*	*		*		*	*	*	*	*
	Power					*	*				*		*	*	*
	Sensors	*	*	*	*	*	*				*			*	
	Zone Cooling/Heating	*			*	*		*			*			*	
	Schedule					*		*					*	*	
	Title 24 Compliant	*	*	?	*				?	*	*	*		*	*

		Lennox Prodigy	Carrier WeatherExpert	Trane Precedent, Reliatel, Intellipak	York Simplicity SE, Predator	Switch Automation	ClimaCheck ConCom	ECore	Ezenics AFDDI	Honeywell Jade	Pelican Wireless Pearl	Johnson Controls Simplicity SE	Virtjoule	XCSpec Economizer Pro	Transformative Wave eIQ
	Faults Prioritized	?	?	?	?	*	*	*	*	?		*		?	*
Where	Embedded	*	*	*	*							*			
	Retrofit Controller							*		*					
	Cloud-Based					*			*				*	*	
	Multiple						*				*				*
FDD Method	Rule-Based	*	*	*	*			*	*	*			*		
	Process History Based														
	Quantitative Model Based											*			
	Mixed					*	*				*			*	*
Communication	Local	*	*	*	*		*			*		*			
	Website					*		*	*		*		*	*	*
	Text					*		*	*		*		*		
	Email					*		*	*		*		*	*	*

		Lennox Prodigy	Carrier WeatherExpert	Trane Precedent, Reliatel, Intellipak	York Simplicity SE, Predator	Switch Automation	ClimaCheck ConCom	ECore	Ezenics AFDDI	Honeywell Jade	Pelican Wireless Pearl	Johnson Controls Simplicity SE	Virtjoule	XCSpec Economizer Pro	Transformative Wave eIQ
	Other					*							*		
Diagnostic Capability Level	1–4, according to NREL categorization	2	1	1	1	2	3	2	1	1	1	1	1	1	2