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AN APPROACH TO BRINGING AUTOMATED FAULT DETECTION AND DIAGNOSIS (AFDD) TOOLS FOR HVAC&R INTO THE MAINSTREAM

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ABSTRACT

Heating, ventilation and air-conditioning (HVAC) systems can consume over 5 quads of energy annually, representing 30% of energy consumption in the U.S. in commercial buildings. Additionally, commercial refrigeration (R) systems add about 2 quads to commercial buildings energy consumption. Most HVAC systems have one or more faults (low/high refrigerant charge, valve leakage, condenser/evaporator fouling, filter/dryer restriction, economizer faults, controls faults) that result in increased energy consumption. Automated fault detection and diagnosis (AFDD) tools have been developed to address this national issue and many tools are commercially available. AFDD tools have the potential to save considerable energy for existing commercial RTUs, chillers and refrigeration systems. These devices can be used for both retro commissioning, and, when faults are addressed, continuous commissioning as well. However, there appears to be multiple market barriers for this technology. A key market barrier for this technology is the lack of awareness of AFDD products among potential customers. Most HVAC contractors are not familiar with the latest AFDD technologies and HVAC technicians lack skills regarding these technologies. Quantifying potential benefits to building owners is difficult since there are several FDD tools with varying capabilities. For instance, there are several FDD products ranging from handling just economizer faults to those that also handle full-blown refrigerant-side and air-side faults. Methods/algorithms used in FDD vary significantly. Even though there are efforts to develop standards, currently there are no standards/methods to define functions, capabilities, accuracy, and reliability of FDD tools. Moreover, most of the commercial AFDD tools have not been verified in the field independently. This paper presents a comprehensive approach to bringing HVAC AFDD tools into the mainstream. The approach involves demonstrating ten commercially available tools at ten different sites, independent testing and evaluation of the FDD tools, communication with various stakeholders, identifying market barriers, and assisting utility companies in developing incentive programs. This paper presents selection of AFDD tools, site identification, and field testing and evaluation method.

Keywords: Heating ventilation and air conditioning, automated fault detection and diagnosis tools, energy, refrigeration, faults, RTU, Building Management System (BMS)

1. INTRODUCTION

Heating, ventilation and air-conditioning (HVAC) systems can consume over 5 quads of energy annually, representing 30% of energy consumption in the U.S. in commercial buildings [1]. Packaged rooftop air-conditioning units (RTUs) provide heating and cooling for over 60 percent of the commercial building space (about 90 billion ft^2) in the U.S. and they are a significant source of energy consumption and peak demand. It is estimated that 40,000 10-ton RTUs are sold each year in the US. There are over 486,000 RTUs in the Northeast region and about 2,700 units sold in 2014 in Connecticut. Another important market segment is commercial refrigeration. It contributes about 1 quad to commercial buildings energy consumption [2].

Most RTUs have one or more faults such as low/high refrigerant charge, valve leakage, condenser/evaporator fouling, filter/dryer restriction, and economizer faults. These faults increase their energy consumption. If these faults are detected, diagnosed and addressed, then significant energy could be saved. Automated Fault Detection and Diagnosis (AFDD) tools have the potential to save considerable energy for existing commercial RTUs. These devices, when installed on RTUs (and other HVAC), can be used for retro commissioning and when faults are addressed, can be used for continuous commissioning. According to [1], national energy savings of 111 TBtu can be saved by employing AFDD tools for commercial RTUs. Faults in commercial

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refrigeration systems not only result in significant energy use but can lead to shutdown of equipment that can cause damage to refrigerated products. Goetzler, et al. [2] indicated that a popular supermarket employed a leakage detection and energy usage monitoring system that reduced electricity use by 23 million kWh per year.

To address this need, countless efforts to develop FDD tools have been ongoing for at least three decades. References [3-8] present just a mere sample of literature that is available on FDD. Now, there are several commercial FDD products marketed by companies. The products include – field-portable FDD tools, factory-installed on-board FDD tools, hardware-based retrofit on-board FDD tools and software-as-a-service (SaaS) FDD tools. However, FDD systems haven't yet achieved a high HVAC market penetration. In an online article titled, "FDD Going Mainstream? Whose Fault is it?" several issues with FDD implementation are listed, such as - lack of data; rules specific to systems; how to handle the FDD information; using the diagnostic data; prognostics data; alternative ways to deploy FDD [9]. A key market barrier for this technology appears to be the lack of awareness of FDD products among potential customers (building owners). Most HVAC contractors are not familiar with the latest FDD technologies and HVAC technicians lack skills regarding these technologies. Quantifying potential benefits to building owners is difficult. Moreover, most building owners look for short-term ROI for their investment. Many of the FDD benefits such as reduced HVAC downtime due to early warning and repairs, avoidance of catastrophic failures, and predictable maintenance will not be so evident to the building owners. FDD technology appears to be like an "unknown saint." It has promise but not fully understood, evidenced, or exploited. To make matters more complicated, many FDD tools are packaged with energy efficiency retrofit kits, and it is not clear to customers which ones to use. Even though there are efforts to develop standards, currently there are no standards/methods to define functions, capabilities, accuracy, and reliability of FDD tools. Also, costs of FDD tools are high and installation costs could be higher as well. Also, it is not clear how the process of FDD installation, communication of faults, severity of faults and actions occurs. It is quite clear that addressing these issues and overcoming these barriers are challenging, but necessary.

In that regard, there is a continued push for bringing FDD products to commercial market. Western HVAC Performance Alliance has been working on FDD Road Map and released a Master List of existing FDD products (over 100) [10]. Some efforts by utilities and Federal and State agencies are underway to bring attention to FDD tools. For instance, California Energy Commission's Title 24-Part 6 [11] requires that economizer fault detection and diagnostic functions (FDD) be installed on air-cooled unitary air conditioning systems over 4.5 tons cooling capacity, with the ability to detect the faults. The current study is a comprehensive approach to bringing automated fault detection and diagnosis (AFDD) into the mainstream.

2. APPROACH

Uniqueness of this study approach is its comprehensive nature. It includes identification of diverse AFDD products, selection of different commercial building types for the field demonstrations, process evaluation, performance verification, determination of technical and economic viability, supporting the development of utility incentives, and education and outreach. Identification of technical and market barriers, and development of strategies to address them by bringing together all stakeholders is the overall objective. These elements are discussed further in the following sections.

3. AFDD TOOL AND SITE SELECTION

3.1 Automated Fault Detection and Diagnosis Tools

The goal is to select 10 different commercially available AFDD tools for the field demonstration study. Therefore, an AFDD tool selection matrix was developed. The matrix included various performance parameters of AFDD such as the tool type (whether hardware-based or SaaS-based), type and range of faults detected, capability to detect heating and cooling faults, feature to diagnose and verify faults, limitation on the size of HVAC system, fault communication and frequency, skill level needed to use the tool, FDD tool pricing, etc. The selection matrix was formatted into a Request for Information (RFI) and sent to several FDD vendors. Responses from 12 vendors were received. Based on the responses, scores for each performance metric were assigned based on importance for the study. The response scores for each metric equated to a total of 1. Next, total scores were calculated to compare with the reference maximum which indicates the highest possible score a tool could receive The results are shown in Table 1 below with a sample weighting snapshot shown above .

Table 1. Overall scoring of FDD tools based on vendor RFI responses (below) and sample weighting (above)

	Weighting	AME
1.1.3 What building size does your product serve? Select all that apply.		
☐ Large > 50,000 square feet (sf)	0.20	
☐ Medium 10,000 – 50,000 sf	0.50	
☐ Small < 10,000 sf	0.30	0.30
Total	1.00	0.30

Reference Tool	Raw Score	Percent	FDD Name &Type
Reference, max	17.89	100%	NA
FDD Tool 1	17.39	97%	AME-Hardware
FDD Tool 2	14.65	82%	Buildpulse- software
FDD Tool 3	16.79	94%	ClimaCheck- hardware
FDD Tool 4	15.29	85%	Tridium-hybrid
FDD Tool 5	16.49	92%	Ecorithm-software
FDD Tool 6	13.37	75%	Enerfit-hardware
FDD Tool 7	15.74	88%	CCI-hybrid
FDD Tool 8	14.54	81%	Ezenics-software
FDD Tool 9	12.92	72%	T-Wave - hybrid
FDD Tool 10	11.60	65%	Virtjoule - hardware
FDD Tool 11	16.44	92%	Coppertree - software
FDD Tool 12	13.64	76%	MSI - hardware

Of these 12 FDD tools, one tool is not market ready and one FDD tool vendor dropped out from the study. Therefore, the study considered the remaining 10 FDD tools for field testing and evaluation.

3.2 Site Selection

The project's target is 10 sites for the field demonstration of the FDD tools. Table 2 shows factors being considered for site selection. A memorandum of understanding (MOU) along with the project scope was sent to several sites directly and through Connecticut utilities (United Illuminating and Eversource). Several site visits were conducted after receiving MOUs to select candidate sites. Out of more than 15 sites, a set of 10 sites were selected and were paired with 10 FDD tools as shown in Table 3.

Table 2. Site selection aspects considered in the study

Site Parameter	Question/Metric for Site
Building Use	Building type
	Year-round use
RTU Characterisitics	RTU characteristics such as
RTU and ductwork access	RTU accessibility
	Ductwork accessibiity for installing sensors for M&V
Building System Characteristics	Building energy management
	Network access
	Recent energy projects
	Status of current building and operations
	Commercial refrigeration
Maintenance Practices	Current RTU service
	Preventative Maintenance
	Complete maintenance
Potential Future Savings Impact	Nationwide chain

Table 3. List of sites for DOE installation

Site	Building Type	FDD tool pairing
United Technologies Research Center	Research Center; office buildings	BuildPulse
University of Connecticut	Academic	CopperTree
Fairfield- Sullivan Independence Hall	Office Buildings	Ecorithm
Chili'	Restaurant	ClimaCheck
Alinabal Inc.	Manufacturing/offices	Transformative Wave
Tyl Middle School	Academic/school	Ezenics
Fairfield Library	Library	Virtjoule
Staples	Retail	SkySpark
Wesleyan University	Academic/school and cafeteria with refrigeration	Pace/Hitachi
S&S Worldwide	Distribution Center	Enerfit
North Haven Health and Racquet Club	Health Club	Tridium

4. FIELD TESTING AND EVALUATION

One key objective of the study is to undertake a comprehensive evaluation of AFDD tools, which is a complex task that requires examination of the FDD tools' performance, cost, ease of implementation, ease of use, data requirements, training requirements, and applicability to the needs of a particular site or customer [12]. A framework proposed by Lin, et al. [13] forAFDD *performance* evaluation was reviewed carefully. The framework is found to be useful for evaluating FDD protocols, but not for evaluating FDD tools in the field under naturally occurring faults, which can vary from no-fault to single faults of varying intensity and frequency, to multiple faults. Therefore, there is no control over some aspects of input samples for the AFDD tools. However, the framework principles are used in the FDD Tool performance verification. For instance, three categories of faults will be considered – 1) condition-based, 2) outcome-based and 3) behavior-based. All these categories are employed by different commercial AFDD tools. Also, ground-truth is employed in the verification of faults by AFDD. Ground-truth will be a combination of independent monitoring of the RTU with essential sensors and instrumentation, and in-field checking of the system, its operation and controls.

4.1 Independent Monitoring System

A comprehensive monitoring system comprising a remotely accessible data acquisition system along with essential sensors and instrumentation has been designed and will be used in the verification process. Below is a list of sensors and instrumentation that are implemented for the verification system. These sensors are capable of measuring both refrigeration side and air side performance. One-minute interval data is stored and can then be accessed remotely through a cellular modem that sends the data to the cloud. This prevents the user from having to return to site every time data is collected. Table 4 presents the specifications for the sensor type and location while and Figure 1 identifies a schematic of an RTU with locations of all the sensors.

Table 4. Sensors and instrumentation used for independent monitoring

Sensor type	Location	Number
Temperature	Suction line	1
	Discharge line	2
	Air side after condenser	3
	Before the expansion device	4
	Air at evaporator outlet before the fan	5
	Supply duct	6
	Return duct	7
Temperature and relative humidity	Mixed air	8
	Outdoor	9
	Indoor	10
	Supply duct averaging	11
	Return duct averaging	12
Airflow	Supply duct	13
Power Meter	Compressor, blower, main	14
Current Transformers	Each leg of compressor, blower, and main	15
Pressure Trasnducer	Suction	16
	Discharge	17

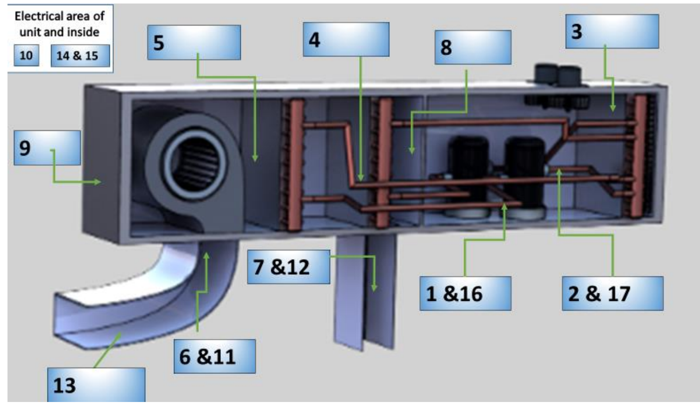

FIGURE 1: A SCHEMATIC OF A ROOFTOP HVAC UNIT WITH LABELS INDICATING SENSOR LOCATIONS

4.2 Post Processing and Fault Verification

The majority of the hybrid tools require a building management system (BMS) to be installed to read the data points within the RTU. BMS are said to be intelligent systems that control and monitor a buildings main technical components such as the HVAC&R and lighting. Since the BMS-based AFDD tools can monitor all the RTU's on a building and it will be more cost effective to study all the units than studying one unit, these tools will monitor all the RTUs on a building. However, the independent monitoring system is installed only on one RTU. For non-BMS, hardware-based AFDD tools, only one AFDD tool will be used along with the independent monitoring system on one RTU per building selected. There are several potential faults that can occur with RTUs and commercial refrigeration and the faults detected by commercial AFDD tools are varying. Some of the faults considered in this study are:

- ☐ Refrigerant charge
- ☐ Condenser fouling
- ☐ Evaporator fouling/insufficient air flow
- ☐ Expansion device
- ☐ Compressor faults
- ☐ Energy performance degradation
- ☐ Refrigerant liquid line restriction
- ☐ Non-condensable gases in refrigerant
- ☐ Economizer
- ☐ Controls
- ☐ Sensor faults
- ☐ Other

Once an AFDD tool and the independent monitoring system are installed, monitoring of the RTU will continue for six to eight weeks under naturally occurring faults. The data from the independent monitoring system will be reviewed weekly subject to the fault detection algorithms [7,14-17] or when the AFDD tool detects faults, whichever comes first. Ground truth for un-faulted condition will be obtained once the identified faults are fixed.

4.3 Measurement and Verification of Energy Savings

To determine the savings in energy due to fault correction, the following calculation can be used

$$Savings(kWh)$$
$$= Faulted\ energy\ use\ (kWh)$$
$$- Unfaulted\ (Retrofit)\ energy\ use(kWh)$$

Similarly, the above equation can be changed for the savings in terms of dollar value, by multiplying the energy usage by the cost of electricity (e.g. $0.12). Taking this process one step further, the annual energy consumptions (and therefore savings) is calculated as well. A simple expression is given below.

$$Annual\ Cost\ savings$$
$$= energy\ savings * rate$$
$$+ \sum month\ (monthly\ demand\ savings$$
$$* rate)$$

In order to calculate energy savings, the energy use data (which is obtained by the independent monitoring system) for faulted and un-faulted (retrofit) scenarios will be correlated with the outdoor ambient temperature or cooling degree-days (CDD) or heating degree days (HDD). An estimate of annual energy savings can be found by using annual CDD and HDD for the location.

5. MARKET BARRIER STUDY

This is an important task for this study. In order to identify market barriers, a preliminary survey was conducted at a stakeholder outreach event in Connecticut in 2018. Table 5 shows a survey of stakeholder responses to questions on the value of energy efficiency.

Table 5. A preliminary survey on value of energy efficiency

FDD for HVAC-R DEMONSTRATION PROJECT	Fault Detection and Diagnostics FDD Project Stakeholder Survey					
	How important are the following value propositions to your organization, customers, or stakeholders when investing in building energy efficiency technologies?					
	Very Important	Important	Fairly Important	Slightly Important	Not Important	Do Not Know
reduced energy consumption	23	4	1	0	0	0
reduced energy demand	19	4	4	1	0	0
reduced energy costs	23	3	2	0	0	0
reduced other utility costs (for example, water, etc.)	12	8	5	2	1	0
facility operations costs	14	12	2	0	0	0
facility maintenance costs	16	9	2	0	0	1
operational performance: customer comfort levels for HVAC-R or product quality for refrigeration	16	9	3	0	0	0
operational performance: cooling qualilty (product integrity, etc.) for refrigeration	13	11	3	1	0	0

It clearly shows that an overwhelming majority of the respondents value building energy efficiency. Table 6 presents another survey on market barriers. Based on the survey results information barriers, organizational barriers and technical barriers appear to be serious in nature.

Table 6. A preliminary survey on FDD market barriers

FDD for HVAC-R DEMONSTRATION PROJECT	Fault Detection and Diagnostics FDD Project Stakeholder Survey						
	How difficult do you perceive each *barrier you or your organization might face in adopting FDD technologies* at your facility or your customers' facilities?						
		Very Difficult	Difficult	Fairly Difficult	Slightly Difficult	Not Difficul	Do Not
Information Barriers	Interpreting and understanding the value proposition	3	5	5	9	5	3
	Lack of understanding of how technology works	0	6	5	12	6	1
	Determining the purchase model	3	6	10	5	2	4
	Determining how best to use contractors and service providers	2	4	7	10	6	1
	Determining how FDD technology fits with higher level energy management practices	0	9	10	7	4	0
Organization Barriers	Change from current decision making, practices, and technologies to select and use a new technology	4	11	4	7	3	1
	Understand how increased operation and maintenance expense can offset value obtained in other areas	6	6	9	4	3	2
	Accepting of some technical and cost risk	3	9	7	7	3	1
Technical Barriers	IT integration and/or data integration	4	8	8	2	5	3
	Communication integration	1	9	9	4	5	2
	Physical integration with common building automation systems	3	7	8	7	4	1
	Physical system integration with other building systems	1	10	7	6	3	3
	Lack of integration standards	5	11	5	5	3	1
	Expensive to implement in smaller buildings	13	9	2	2	2	2

Based on this input, detailed market barrier surveys aimed at different stakeholders (building owners/facility managers; HVAC contractors/energy consultants/utilities) are being developed. It is contemplated that results of these surveys will be presented elsewhere.

6. RESULTS AND DISCUSSION

As of June 2019, independent monitoring systems and FDD tools were installed at nine sites in Connecticut. Sample photos of installations are presented in Figures 2 through 5. Figure 2 shows a snow-covered rooftop at Alinabal manufacturing facility in Milford, CT. Transformative Wave's Catalyst eIQ is the FDD tool installed at this site (shown in Figure 3).

FIGURE 2: A PHOTO OF AFDD INSTALLATION AT ALINABAL IN MILFORD, CT.

FIGURE 3: A PHOTO OF TRANSFORMATIVE WAVE'S CATALYST eIQ INSTALLED AT ALINABAL IN MILFORD, CT.

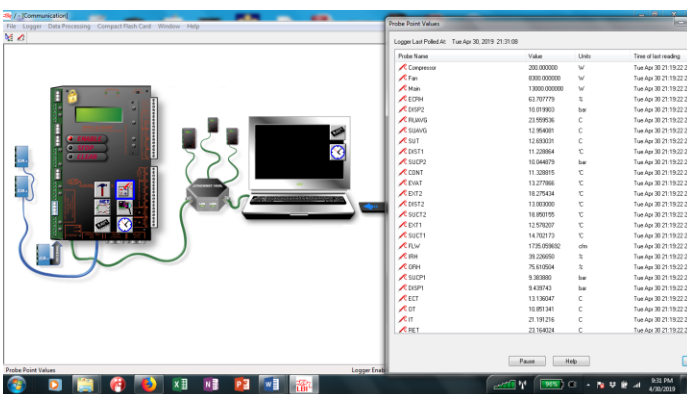

FIGURE 4: A SCREEN-SHOT OF WEB-ENABLED DATALOGGER AND REAL-TIME DATA.

Catalyst eIQ is a hardware-based tool. A trained technician was able to install in less than 4 hours. The independent monitoring system was installed over two days. Figure 4 shows the web-enabled datalogger with real-time data for the independent monitoring system.

Another hardware-based AFDD tool, ClimaCheck, was installed at Chili's restaurant in Milford, CT (see Figure 5). This installation proved to be a difficult installation due to limited access to ductwork in the attic space and the space within the RTU was restricted to place sensors. Also, installing refrigerant pressure sensors was tedious. The installation was completed over a day and a half, including troubleshooting time.

FIGURE 5: A PHOTO OF CLIMACHECK AFDD TOOL INSTALLATION AT CHILI'S IN MILFORD, CT.

Currently, all but one installations at other locations are completed. For some locations like Chili's Restaurant, fault alarms are already being sent on a daily basis. For the other installations that are complete, data is being collected to verify all the sensors are connected and working properly. When irregularities in sensor data are identified, additional visits to the sites are made to rectify the errors. Additionally, the other FDD companies are currently in the process of collecting data points and verifying the analysis as well as baselining for hotter summer days. The measurement and verification (M&V) of AFDD will be undertaken after troubleshooting. Results of M&V will be presented in another publication.

7. CONCLUSIONS

The importance of automated fault detection and diagnosis (AFDD) tools and the need for a comprehensive approach to bring the AFDD tools into the mainstream are highlighted. The approach involving AFDD field demonstrations and market barrier study are presented.

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