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ABSTRACT

An ongoing project is collecting data from multiple vendors of fault detection and diagnosis (FDD) software. We have a dataset of over 12 months from each FDD partner. The project is harmonizing the FDD outputs and aggregating these results for all of the vendors, to have a dataset on which analyses can be conducted to shed light on questions like: which faults are most commonly reported; how frequently each fault type is reported; whether faults correlate with drivers such as geographical region, building type, and others. In order to better understand the error of fault reporting by FDD, field validation has been carried out on a small subset of those buildings for which FDD outputs were gathered. This allows verification of the presence of flagged faults, and checking for faults that were not flagged by the FDD tools. More importantly, it provides insight into some of the challenges of using FDD data in a study of this kind. This paper describes the process of field verification, and preliminary results from the site visits. These site visits were conducted on two retail buildings that are each served by multiple rooftop units (RTUs). Examples of the types of faults that were encountered in the field include: stuck/disabled economizer dampers, disconnected or non-communicating sensors, non-condensable gas in the refrigerant, sensor drift or bias, and loose fan belts.

In the field study there were cases of faults being reported when they weren't actually present, faults that were present that went unreported, and faults that were present, but are not a type of fault that the FDD tool attempts to diagnose. The sample size for the results in this paper – 49 RTU in two buildings monitored by one FDD tool – is not sufficient to be able to make any generalizations about the commonality of a given fault. However, the results show that the FDD results for some faults are less useful than others. For example, in one building all 27 CO_2 sensors are classified as being faulted, but inspection showed that there are no CO_2 sensors installed. Thus, these field results play into the broader objectives of the project. The work is ongoing, so this paper is intended to share early results with the buildings community and gather feedback.

1. INTRODUCTION

Packaged rooftop units (RTUs) are widely used in commercial buildings in the United States. They serve the heating, ventilation, and air-conditioning (HVAC) requirements for about half of the United States commercial building floor space (DOE, 2011). Unfortunately, they are believed to operate below their rated efficiencies because of faults introduced during installation or developed during operation (Feng *et al.*, 2005). Therefore, significant energy is wasted as a result of the presence of operating faults in RTUs that go unnoticed by the owners or operators of the equipment. A solution to address this problem is to apply fault detection and diagnosis (FDD) tools to RTU systems so that important faults can be identified and addressed promptly. Although there is a significant growth in the use of

FDD tools, and a growing body of research on their energy saving benefits, there is still a lack of consistent and reliable data on exactly what these tools are finding.

Many FDD tools rely on building automation system (BAS) data to detect the presence of HVAC faults and support diagnosis of their root causes. Applying FDD tools in commercial buildings and correcting the identified faults can save 9% of energy consumption (Kramer *et al.*, 2020). Faults in the United States commercial buildings waste approximately 0.9–2.7 quads of energy annually (Frank *et al.*, 2019). However, this energy waste estimate is based on uncertain estimates of actual fault prevalence in the field. There is a lack of reliable data about prevalence, and even a lack of metrics to describe the prevalence of HVAC faults.

Some studies in the literature have discussed prevalence of faults in RTUs. Breuker and Braun (1998) estimated the frequencies of occurrence and the service costs of different RTU faults by analysis of service records of a company from 1989 to 1995. About 6,000 service records were analyzed in order to determine the common faults in RTUs, and estimate their energy impacts. They found that 60% of faults that resulted in service calls were electrical or control problems, while 40% of faults were related to mechanical problems.

Felts and Bailey (2000) monitored and analyzed over 250 RTUs installed in small commercial buildings in northern California. The monitoring period was three summer months, and each unit was monitored for three to five days. This study concluded that 40% of the RTUs were more than 25% oversized, and 10% of the RTUs were more than 50% oversized. It was also shown that economizers generally did not operate correctly.

Davis *et al.* (2002a; 2002b) developed a field protocol to evaluate the performance of RTUs in small commercial buildings, and applied it to 30 RTUs in Oregon, in the United States. Their field results found that only 36% of the units had the correct amount of refrigerant charge. They also found that about 67% of the RTUs had evaporator airflow less than 350 SCFM/ton, and only less than 40% of economizers were fully functional.

Cowan (2004) investigated data from 503 RTUs at 181 commercial building sites across five states - Oregon, Washington, Idaho, Montana, and California - that had been gathered in four field studies. It was found that 46% of the units had improper refrigerant charge, 64% of the units had economizer problems, 42% of the units had airflow problems, 58% of the units had thermostat problems, and 20% of the units had sensor problems.

Shoukas *et al.* (2020) analyzed the fault data collected from FDD tools provided by four companies, representing over 28,000 RTUs, to determine the frequency of the reported faults. Since different companies use different formats, fault definitions, diagnosis, and reporting, they were not able to compare between FDD tools, and results were presented separately for each data provider. They concluded that the frequency of the faults depends on the fault definitions and the diagnosis methods. They found that RTU faults occurred most commonly on economizer dampers, sensors, communications, and cooling systems.

Katipamula *et al.* (2021) analyzed the BAS data from 151 US commercial buildings to find their operational problems and opportunities. They concluded that the state of current commercial building operations results in 30% excessive energy consumption. This study showed that opportunities to improve building operations exist in almost every commercial building. The prevalence of the top 20 re-tuning opportunities ranged between 23% and 74%.

Kim *et al.* (2021) performed a literature review to summarize studies which have characterized fault prevalence in commercial buildings. They focused on three fault occurrence metrics in their review: fault prevalence, fault incidence, and percentage of fault among all faults. They found that fault occurrence metrics change significantly between different studies. For example, the prevalence of improper refrigerant charge fault was reported between 30% and 70% in different studies. The review identified knowledge gaps in current literature on fault prevalence, and recommended a comprehensive study on HVAC fault prevalence in commercial buildings to fill these potential gaps.

Ebrahimifakhar *et al.* (2021) described a method to estimate the prevalence of HVAC faults in air handling units (AHUs), air terminal units (ATUs), and rooftop units (RTUs). The primary source of data for this study comes from commercial FDD software tools. This is because commercial FDD software outputs can be obtained for a large number of buildings and HVAC systems at a relatively low cost. They described how the data from multiple data providers can be processed and unified using a common taxonomy, and illustrated HVAC fault prevalence metrics that can provide insights using this type of data. They provided preliminary data to illustrate their HVAC fault prevalence metrics.

FDD software results inherently have some level of error, i.e., they might miss faults that exist in the monitored system, report faults that do not actually exist, or misdiagnose the nature of a fault. In order to better understand the gaps between faults reported by FDD tools and the true presence of faults, and gain more insights into the how this can affect the predicted prevalence of fault types, field verification has been carried out on two buildings for which FDD data were collected. This allows verification of the presence of flagged faults, and checking for faults that were not flagged by the FDD tools. The site visits were conducted on retail buildings that are each served by multiple RTUs.

Commercial FDD tools are designed to work with a practical set of constraints. For example, they might be designed to avoid false alarms, even at the cost of imposing missed detections (false negatives), and to focus on HVAC faults that are most cost-effective to detect. A significant challenge of commercial FDD providers is to make sense of the building automation system (BAS) points, which provide the inputs for FDD algorithms. For some fault types, there are not sufficient sensors to be able to detect them. For example, non-condensable gas in the refrigerant and loose fan belt faults are typically not targeted by FDD providers, but can easily be found with field measurements. As efforts to standardize the identification of BAS data and metadata (ontologies) progress, the barriers to adoption are shrinking and opportunities for consistent FDD are expanding. The issue of the accuracy and utility of diagnostic outputs is expected to become increasingly important in this context.

In this study, two field verification methods were employed to analyze the discrepancy between the faults reported by FDD tools and the ones that truly exist. One verification method is to do manual analysis of BAS data to determine HVAC faults that were not detected by the FDD software. Another verification method was manual inspection of buildings, i.e., field testing. This method provides the highest fidelity verification. However, it also has the highest cost. Therefore, it was only applied to a small subset of the buildings in the broader study.

2. METHODOLOGY

In this study, two buildings were subject to site visits, which have a total of 49 RTUs. Details of the site and equipment are described in Table 1. Each building has a BAS that monitors and controls the operation of the RTUs.

Table 1: Descriptions of sites and equipment in field study

Building ID	Building Type	Building Age (years)	# RTUs	Capacity (Tons)
1	Mercantile	18	27	2-13
2	Mercantile	11	22	7.5-17.5

For field verifications, four approaches were used: 1) Monitoring data from the BAS system of the subject buildings; 2) Field measurements and observations (single point in time); 3) Short term data logging; and 4) Functional performance testing (e.g., commanding a damper open to see if it moves).

This paper focuses on the challenges that the FDD tool had, rather than listing all of the correct outcomes – either with correctly identifying faults that existed, or not flagging faults when they didn’t exist. The discussion analyzes the following faults: sensor faults, economizer damper stuck, non-condensable gas, and abnormal supply fan belt tension. The FDD tool monitoring the building is designed to find only the first two of these four fault types. In the following subsections, the methods for detecting these faults are explained. One goal of this study is to compare the field study findings with the reports of the FDD tool already installed in the buildings; the second goal is to see whether there is a significant incidence of fault types that are not monitored by some or all FDD tools. Finally, we were interested in better understanding some FDD outputs that were unexpected.

2.1 Sensor Faults

In order to detect and diagnose sensor faults, time series data obtained from the building's BAS are compared to corresponding measurements from our data loggers. Inaccurate sensor readings can cause an RTU to operate in a way that is wasteful of energy (e.g., a mixed air or outdoor air temperature sensor fault can cause the economizer to operate poorly) or harmful to thermal comfort (e.g., a zone temperature sensor fault can cause a zone to be too warm or too cool). The data that is collected by the loggers is considered as the ground truth for this study, and was often verified with a single point measurement when the logger was being installed. The fault categorizations come from Chen *et al.* (2021). If there is a mismatch between BAS and data logger that is nearly constant over time, the fault is categorized as a sensor bias. If the difference between the values is not nearly constant over time, the fault is categorized as a sensor drift. If BAS value is constant over time but the true value changes, the fault is categorized as a frozen sensor. Supply air, mixed air, return air, and zone temperature sensors were checked in this study. Figure 1 shows an example of a data logger sensor attached to the side of the BAS's zone temperature and relative humidity sensor housing.

Figure 1: Data logger sensor beside the BAS's zone temperature and relative humidity sensor

2.2 Economizer Damper Stuck

The literature discussed in the introduction indicated that RTU economizers often fail to function properly because of damper, sensor, and other faults presented in the unit. Economizer faults might go completely unnoticed for long periods, which can increase the system energy consumption. For example, an outdoor air damper stuck open will require significant additional cooling in hot weather or heating in cold weather. If the damper is stuck closed, the RTU will miss economizing opportunities in mild weather. In this study, the stuck economizer damper fault was checked by commanding the damper to open and close from the unit controller in the field, to visually check the damper operation. If the damper does not modulate when it is commanded open or close, then an economizer damper stuck is identified. Typically, we would further investigate to understand the root cause, such as a wiring problem or mechanical failure. For example, Figure 2 shows the economizer section of an RTU in the field study that did not modulate because its actuator was disconnected.

Figure 2: RTU economizer fault caused by disconnected actuator plug

2.3 Non-Condensable Gas

Non-condensable gases, such as air and nitrogen, might enter an RTU during installation or servicing if the refrigerant circuit is not fully evacuated prior to refrigerant charging. Non-condensable gas tends to accumulate in the unit's condenser (Li and Braun, 2007). It increases compressor power usage, because its partial pressure is added to the pressure of the refrigerant in the condenser, adding to the compressor lift, thereby reducing the system's efficiency. When the RTU is off and two-phase refrigerant exists within the unit's condenser, the non-condensable gas adds a partial pressure, so that the total pressure is higher than the saturation pressure of the refrigerant. A difference between the measured temperature and the saturation temperature (calculated from the measured condenser pressure) indicates the presence of non-condensable gas. When the saturation temperature is more than 1.7 °C (3 °F) higher than the condenser temperature, we conclude that a non-condensable gas fault is present (Hu *et al.*, 2021).

2.4 Abnormal Supply Fan Belt Tension

Reduced tension in an RTU supply fan belt can allow the belt to slip and transfer less mechanical energy from the motor to the fan. Therefore, for a given motor speed, the airflow rate will be lower. Over-tensioning can result in excessive stress on belts, leading to a reduced bearing or belt life. To detect and diagnose whether the belt has incorrect tension, the force-deflection method was used. Belt cross section (e.g., BX), belt span, smallest sheave diameter, and belt deflection force are collected in the field, and by comparing the applied force with the rated belt tension, the fault was diagnosed.

3. RESULTS

Using the fault detection and diagnosis methods described in the previous section, the actual RTU faults in the two buildings are identified and discussed in Section 3.1 and 3.2. A comparison of the results of the field study with the FDD fault reports is performed to uncover any cases of false alarms and missed detections, as well as to gain more insights into the performance of the existing FDD tools. Examples of analysis methods are shown in Section 3.1.

3.1 Building 1 Results

Building 1 has 27 RTUs, which were monitored from March 4 to March 12, 2021. Table 2 shows data gathered from the FDD provider fault report for the same period, along with percentages describing comparisons of FDD output and site visit determinations. The numbers of units reported by the FDD as faulted with sensor faults are high. A manual inspection of the BAS data showed that it contained some columns of zero values for sensor readings. The FDD algorithm classified the zero values as sensor frozen faults, but a physical inspection showed that either the sensor did not exist, or was not connected. These faults are therefore classified as false alarms (false positives) of the FDD software, since a fault is identified while no fault is present. The last row shows the "economizer damper stuck" fault, for which the FDD tool did not detect the fault in two RTU where it occurred. These are classified as *missed detections* of the FDD tool. For practical reasons, the site visit did not include physical investigation of every RTU for every fault type.

Table 2: Comparison of FDD outputs and site visit outcomes for Building 1

Fault Name	# RTUs checked	FDD fault reports	Site visit fault reports	FDD false alarms (percentage)	FDD missed detections (percentage)
Mixed air temperature sensor frozen	27	27	0	27 (100%)	0
Return air temperature sensor frozen	27	27	0	27 (100%)	0
Return air CO_2 sensor frozen	27	27	0	27 (100%)	0
Zone relative humidity sensor frozen	27	21	0	21 (78%)	0
Economizer damper stuck	10	0	2	0	2 (100%)

Table 3 shows the faults that were identified in the field validation study but are not targeted by the FDD tool. Classifying this outcome is less clear than the earlier outcomes, because although the FDD missed detecting these faults, as in a *missed detection*, it is not the same as missing faults that the FDD is intended to find. Earlier work on evaluating FDD outputs, by Yuill and Braun (2013), gave a category "no response" to cases like this.

The number of RTU with abnormal supply fan belt tension – 7 of 10 – is high. However, this fault and the non-condensable gas fault are both quite dependent upon the technician that installed the system, so the sample size for one building is not sufficient to draw general conclusions. If a broader field study is undertaken, it could identify whether faults should be added to FDD capabilities, based upon whether they are common and impactful.

Table 3: Faults identified that are not targeted by the FDD tool in Building 1

Fault Name	# RTUs Checked	# Faulted RTUs (percentage)
Zone air temperature sensor bias	11	3 (27%)
Non-condensable gas	19	1 (5%)
Abnormal supply fan belt tension	10	7 (70%)

Figure 3 shows an example of both healthy and faulted zone air temperature sensors, illustrating the mode of field validation in which time series measurements from the BAS are compared to measurements from data loggers (considered as ground truth). If the difference between the values is higher than the 1.1 °C (2 °F) detection threshold, and is nearly constant over time, the fault is categorized as a sensor bias.

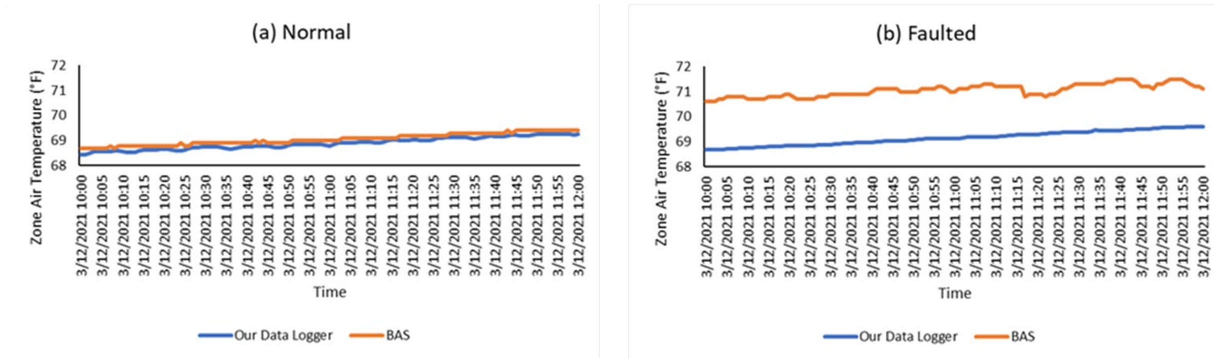

Figure 3: Zone temperature sensor faults identified as: (a) Normal; and (b) Faulted (bias)

Table 4 shows some examples of measurements and fault classifications of RTUs with and without non-condensable gas in their refrigerant circuits.

Table 4: Examples of RTUs with and without non-condensable gas

Unit	Refrigerant Pressure (kPa)	Saturation Temperature (°C)	Condenser Temperature (°C)	ΔT (°C)	Diagnosis
RTU 09	769.5	18.4	15.3	3.1	Faulted
RTU 13	704.6	15.7	15.3	0.4	Normal

Table 5 shows some examples of data from RTUs with normal and abnormal supply fan belt tension. A belt tension checker was used to detect this fault.

Table 5: Examples of RTUs with normal and abnormal supply fan belt tension

Unit	Belt Cross Section	Smallest Sheave Diameter (m)	Fan Speed (RPM)	Actual Belt Deflection Force (N)	Normal Belt Deflection Force (N)	Diagnosis
RTU 06	BX	0.11	1735	15.6	21.8-32.0	Faulted (loose)
RTU 09	BX	0.11	1735	27.6	21.8-32.0	Normal

3.2 Building 2 Results

Building 2 has 22 RTUs. The monitoring time was from March 26 to April 13, 2021. Table 6 lists the faults reported by the FDD tool in this time period. Similar to Building 1, a large percentage of RTUs had faults flagged for frozen sensors. Again, columns of zeros in the BAS data are the source of many or all of the frozen sensor faults.

Table 6: Comparison of FDD outputs and site visit outcomes for Building 2

Fault name	# RTUs checked	FDD fault reports	Site visit fault reports	FDD false alarms (percentage)	FDD missed detections (percentage)
Supply air temperature sensor frozen	22	14	0	14 (64%)	0
Return air temperature sensor frozen	22	11	0	11 (50%)	0
Return air CO_2 sensor frozen	22	22	0	22 (100%)	0
Zone dewpoint sensor frozen	22	15	0	15 (68%)	0
Economizer damper stuck	22	3	6	0	3 (50%)

Table 7 shows the results of the faults that were not targeted by the FDD tool in Building 2. Some RTUs have multiple refrigerant circuits, so the table's entry for # RTUs checked for non-condensable gas refers to the number of circuits checked. Abnormal supply fan belt tension is the most common fault in the Building 2 RTU we investigated, similar to what was found in Building 1 (Table 3).

Table 7: Faults identified but not targeted by FDD tool for Building 2

Fault Name	# RTUs Checked	# Faulted RTUs
Zone air temperature sensor bias	11	0
Non-condensable gas	30*	0
Abnormal supply fan belt tension	18	10 (56%)

*Number of refrigerant circuits checked

4. DISCUSSION AND CONCLUSIONS

This paper showed the results of conducting measurements on two buildings that have FDD monitoring, in order to better understand the FDD results that provide a much larger sample of buildings than could be studied through site visit measurements. The measurements showed that there is not an exact relationship between the reported fault and the actual faults. There are three categories of discrepancy:

1. Faults that are reported by the FDD tool, but are not actually present (false alarms). This study found false alarms in both RTU that had economizer faults reported in Building 1; in each case the economizer was operating correctly. There also was a large number of sensor faults that were flagged for sensors that are not present. In Building 1, for example, the FDD reported that 100% of the RTU had faults in supply air temperature sensors, return air temperature sensors, and CO2 sensors, when in fact these sensors did not exist.

2. Faults that are actually present, but are not reported by the FDD (missed detections). In Building 2, for example, 3 RTU had an economizer fault that was not reported by the FDD.

3. Faults that are present, but are not reported by the FDD tool because it is not attempting to detect the fault type. For example, in Building 2, 10 of 18 RTU were found to have supply fan belt tension faults, but this is not a fault that the FDD monitors or reports.

Conducting field verification is a labor-intensive process, and requires cooperative building managers and owners. It would be a difficult endeavor to generate fault prevalence data through field studies, because the required sample size for an acceptable level of uncertainty would be very large. The work reported in this paper is part of a larger effort to provide an improved understanding of fault prevalence in commercial buildings (Crowe *et al.* 2022), in which a large set of FDD provider data were gathered. The field study was intended to improve our understanding of the meaning and limitations of the FDD data that we gathered. The results presented in this study are from a very limited sample, but they show that the connection between FDD results and true fault presence can be somewhat uncertain. These results are from a single FDD provider, so ongoing work will similarly examine results from site visits to buildings monitored by other FDD providers.

Although some results may seem discouraging, it should be noted that a large-scale study of buildings by Kramer *et al.* (2020) showed that significant whole-building energy savings have resulted from adoption of FDD. The algorithms and user interfaces of FDD tools continue to evolve and improve at a rapid pace. For example, advanced FDD tool developers recognize that facilities managers may receive an overwhelming number of alarms, so they provide effective tools to prioritize them, which may consider the certainty of the diagnosis, among other factors.

In addition to similar analyses for other FDD providers, field verification of faults is also being conducted on buildings served by air handling units and air terminal units in the current project. However, the sample size of buildings is still relatively small. Therefore, we recommend for future work that larger field studies be conducted for a statistically valid sample size of buildings, and that the FDD results and field verification studies consider chiller, boiler, and hydronic distribution system faults.

NOMENCLATURE

AHU	air handling unit
ATU	air terminal unit
BAS	building automation system
BX	belt cross section
FDD	fault detection and diagnosis
HVAC	heating, ventilation, and air-conditioning
RTU	rooftop unit
SCFM	cubic feet per minute of standard air

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