Fault Detection and Diagnostic Software

ET Project Number: ET11PGE3131

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Issued: December 17th, 2012
ACKNOWLEDGEMENTS

Pacific Gas and Electric Company’s Emerging Technologies Program is responsible for this project. It was developed as part of Pacific Gas and Electric Company’s Emerging Technology – scaled field placement program under internal project number ET11PGE3131. Enovity, Inc. conducted this technology evaluation for Pacific Gas and Electric Company with overall guidance and management from Mark Haberman. For more information on this project, contact Mark Haberman MSHS@pge.com.

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# Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AHU</td>
<td>Air Handling Unit</td>
</tr>
<tr>
<td>CFM</td>
<td>Cubic Feet per Minute</td>
</tr>
<tr>
<td>BAS</td>
<td>Building Automation System</td>
</tr>
<tr>
<td>DSL</td>
<td>Digital Subscriber Line</td>
</tr>
<tr>
<td>FDD</td>
<td>Fault Detection and Diagnostics</td>
</tr>
<tr>
<td>IPMVP</td>
<td>International Performance Measurements and Verification Protocol</td>
</tr>
<tr>
<td>MAT</td>
<td>Mixed Air Temperature</td>
</tr>
<tr>
<td>M&amp;V</td>
<td>Measurement and Verification</td>
</tr>
<tr>
<td>OAT</td>
<td>Outside Air Temperature</td>
</tr>
<tr>
<td>RAP</td>
<td>Random Access Point</td>
</tr>
<tr>
<td>RFP</td>
<td>Request for Proposal</td>
</tr>
<tr>
<td>SAT</td>
<td>Supply Air Temperature</td>
</tr>
<tr>
<td>SATSP</td>
<td>Supply Air Temperature Set Point</td>
</tr>
<tr>
<td>SFSPD</td>
<td>Supply Fan Speed</td>
</tr>
<tr>
<td>VAV</td>
<td>Variable Air Volume</td>
</tr>
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EXECUTIVE SUMMARY

This report presents the results of the emerging technologies study on Fault Detection and Diagnostics software.

PROJECT GOAL

This research project aims to evaluate a Fault Detection and Diagnostics (FDD) product capable of identifying problems associated with the operation of HVAC systems commonly used in commercial buildings including air-handling units, variable air volume (VAV) boxes and chilled water systems.

The objective of this document is to present the findings of this research effort including:

- An independent energy baseline and analysis for each test site to determine if magnitude of energy savings reported savings by FDD software is realistic
- A summary of the FDD system installation process and associated initial costs of ownership
- A compiled list of identified faults with analysis indicating if a fault could be validated independent of the FDD software
- Development of energy efficiency and demand response savings models used to compare the energy savings reported by the FDD system with manually generated assessments
- A generalized problem finder tool specification for candidate HVAC systems
- A fault detection and diagnostics tool specification
- Lessons learned from the field assessment of FDD software

PROJECT DESCRIPTION

Three demonstration sites were selected for the emerging technology study, based on building size, existence of a network enabled building automation system (BAS) and the availability of control points found in a typical HVAC system. The FDD systems were deployed at each site which included installation of a data acquisition device capable of receiving trend data from the BAS and transmitting it to a remote database operated by the FDD software vendor.

Before the FDD software was able to generate actionable faults, the systems required a process referred to by the FDD vendor as "on-boarding." On-boarding is an information and data collection process undertaken by representatives from the FDD provider who review building plans, gather sequences of operation for affected systems, and interview stationary and controls engineers to document the operational characteristics of the building. This process is required for FDD system to be configured according to the unique systems and operating schedule of each system.

Once the FDD system was successfully configured and able to generate actionable results, the faults were accessed from a web-based dashboard hosted by the FDD vendor. The list of active faults were regularly reviewed to establish the validity of each result, the potential for
energy savings if the indicated issue was fixed, and cost estimates for repairing the issue. Once a sufficient number of faults had been validated, a summary of the results were presented to the chief engineer and building management to document the energy saving opportunities available at each facility.

The structure of the fault review process varied depending on the complexity of the associated system, the prioritization criteria employed by the chief engineer to determine which faults required the most attention, and the amount of time required to independently validate the existence and severity of a given fault. As a general rule of thumb, high availability and critical systems, such as air-handling units and chilled water systems, where given the most attention during this process. VAV box related faults, while important for addressing tenant comfort issues, were routinely given a lower priority given the potential associated energy savings and labor required to validate each fault.

**PROJECT FINDINGS/RESULTS**

The FDD system was installed at two test sites. A third facility was initially identified as a potential candidate; however, due to the capability of the FDD hardware and the existing BAS controllers the building was not included in the study.

Initial costs for each of the test sites include a 1 year subscription cost of $0.19 per square foot which includes the tally of faults and analysis reported by the FDD web-application. Installation costs for each test sites, including the product subscription cost; labor; and time and materials are as follows:

- Test Site A (269,000 ft²): $53,000
- Test Site B (420,000 ft²): $94,500

A total of 496 faults were identified at the first test site (Test Site A) during the course of the 6 month monitoring period. Due to connectivity issues between the facility and the remote FDD system, ongoing investigation and validation of the faults have not been completed at this time. At this time the FDD system has reported $66 dollars in estimated wasted energy in 6 months for faults with a cumulative wasted energy cost over a threshold greater than $20. The FDD vendor has indicated that a total wasted energy cost for the site is $230. The majority of faults were related to the air handler, central plant and VAV box temperature and airflow sensors being out of calibration or a VAV box not controlling to set point. While an initial collection of faults were identified at the facility, communication between the facility’s BAS and the remote FDD system was disrupted due to a network security breach. As a result, ongoing, independent validation of the faults could not be completed and continued operation of the FDD system was not restored.

At the second test site a total of 349 faults were identified by the FDD system for a total of $800 in wasted energy for a period of 6 months for faults with a cumulative wasted energy cost over a threshold greater than $20. The FDD vendor has reported that a total wasted energy cost of $1,670 during this period. Issues affecting air-handling units amounted to 115 faults, of which, 17% corroborated a known issue. A remaining 11% are still under investigation and 25% were invalidated because it is suspected the fault logic is assuming incorrect system operation. A total of 215 variable air volume box faults were identified. Engineers at the facility have reviewed 46% of these faults with the remaining 54% still under investigation. Of the faults reviewed, 14% were removed from the system due to adjustments made to the FDD system by the vendor and another 12% have been sent to the vendor’s technical staff for questioning and remain as outstanding issues.

As a result of the faults identified by the FDD system, which confirmed the existence of known issues at the Test Site B, three energy efficiency measures have been proposed to
building management with electricity savings of 123,000 kWh/yr, natural gas savings of 600 therms/yr which will yield annual energy cost savings of $18,400. The total project cost is estimated at $94,900 with a utility incentive of 11,700 which translates to a simple payback of 4.5 years. Facility management has yet to indicate if the project will receive a budget for implementation.

PROJECT RECOMMENDATIONS

A list of installation and customer acceptance issues with the FDD system are discussed in detail and indicate that compatibility with older building automation system control protocols was a problem at one of the test sites and connectivity between the FDD system and each of the two other test sites were recurring issues. Additionally, key customer acceptance issues included the following:

- lack of transparency of the underlying fault logic including the set points and system attributes used for asserting if a system is behaving outside of expected conditions
- independent validation and prioritization of faults is labor intensive due to the large number of faults and the limited information provided by the FDD system for each fault instance
- complexity of translating faults into energy savings opportunities that comply with utility sponsored incentive programs

As a result of the lessons learned from the research effort, two specifications are provided. The first specification outlines a Problem Finder Tool to be used for future projects interested in identifying issues with air-side and chilled water HVAC systems. The goal of the specification is to provide a simplified approach for translating issues in to standardized energy efficiency measures. A second specification describes a generalized FDD tool specification which incorporates requirements that address lessons learned from this research project.

TEST SITE BASELINES

Whole building and system-level baselines for each test site are presented in order to:

- Identify the systems present in each building that were monitored by the FDD system
- Note existing energy efficiency issues at these sites that have been identified without the use of the FDD system
- Establish the magnitude of annual energy use at each site in order to normalize the potential savings reported by both the FDD system and by independent verification

Initial baseline models were created and analyzed for each of the sites where the FDD system was deployed. Monthly electricity and natural gas data have been collected from each facility’s existing PG&E meters and hourly weather observations have been collected from nearby NOAA weather stations as the basis for each model. The energy models for electricity use, electricity demand and natural gas use are based on cooling degree days (CDD65) and heating degree days (HDD65), respectively.
The models have been developed using a Whole Building approach (IPMVP, Option C, 2010). Furthermore, the validation criteria1 presented in ASHRAE Guideline 14-2002 have been used to calculate the fractional savings uncertainty of each model as a function of the measurement and verification (M&V) period and the percent of predicted energy savings. When these models are used to quantify energy savings between the baseline and post-retrofit periods, there is an inherent amount of uncertainty in the verification process. Therefore, it is important to quantify the uncertainty of each model in order to assert that energy savings for this project can be adequately measured and verified using the Whole Building approach.

Lastly, qualitative system-level baselines are provided along with descriptions of the corresponding systems. These baselines are composed of potential energy efficiency measures garnished with the results of scoping audits and detailed investigations conducted at each facility.

**Test Site A**

Test Site A is an office and courthouse located in San Jose, CA. The site is composed of two buildings: a 5 story courthouse and an adjacent 3 story office building. Both buildings were erected in 1983.

The courthouse contains offices, judges’ chambers and courtrooms. The Office building is comprised of offices, circulation corridors and support spaces. The building composition is steel frame with stucco exterior and single pane glazing.

**Whole Building Baseline**

A summary of energy use for Test Site A is shown in Table 1. The baseline period is 2/1/2011 – 1/1/2012, which spans a full year of the most recent utility bill data available.

<table>
<thead>
<tr>
<th></th>
<th>(per square foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual Electricity</strong></td>
<td></td>
</tr>
<tr>
<td>Consumption</td>
<td>2,266,142 kWh/yr</td>
</tr>
<tr>
<td></td>
<td>8.4 kWh/ft²</td>
</tr>
<tr>
<td>Maximum Demand</td>
<td>661 kW</td>
</tr>
<tr>
<td></td>
<td>2.5 W/ft²</td>
</tr>
<tr>
<td>Cost</td>
<td>164,597 $/yr</td>
</tr>
<tr>
<td></td>
<td>0.61 $/ft²</td>
</tr>
<tr>
<td>Cost/ Unit</td>
<td>0.073 $/kWh</td>
</tr>
<tr>
<td><strong>Annual Gas (Natural Gas)</strong></td>
<td></td>
</tr>
<tr>
<td>Consumption</td>
<td>32,710 therms/yr</td>
</tr>
<tr>
<td></td>
<td>0.12 therms/ft²</td>
</tr>
<tr>
<td>Gas Cost</td>
<td>28,498 $/yr</td>
</tr>
<tr>
<td></td>
<td>0.11 $/ft²</td>
</tr>
<tr>
<td>Cost/ Unit</td>
<td>0.87 $/therm</td>
</tr>
<tr>
<td><strong>Total Annual Energy Cost</strong></td>
<td></td>
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<tr>
<td></td>
<td>193,095 $/yr</td>
</tr>
<tr>
<td></td>
<td>0.72 $/ft²</td>
</tr>
</tbody>
</table>

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1 ASHRAE Guideline 14-2002 provides validation criteria for energy models using the Whole Building approach. The information is highly detailed and therefore beyond the scope of this report.
Monthly energy use and cost data are plotted in Figure 1. The energy use profile for electricity is relatively constant throughout the year. Monthly costs variation throughout the baseline year can be attributed to periods of increased peak use during the summer months.

**FIGURE 1. TEST SITE A: MONTHLY ELECTRICITY USE**

Maximum monthly demand is shown in Figure 2. Demand remains relatively constant during most months, at just above 600 kW, except for during January and February.

**FIGURE 2. TEST SITE A: MONTHLY ELECTRICITY DEMAND**

Monthly natural gas use is shown in Figure 3. Natural gas use shows noticeable seasonal variation with high usage during the cool winter months and low usage during warmer summer months.
Figure 4 represents the fractional savings uncertainty\(^2\) for electricity usage (kWh) versus the number of months of Measurement and Verification (M&V) at a confidence level of 68%. For example, for electricity savings of 5% the fractional savings uncertainty is 90% for an M&V period of 2 months. Additional combinations of M&V length and expected savings can be used to understand the resulting fractional uncertainty of the expected savings.

\(^2\) Fractional savings uncertainty is the ratio of uncertainty in the model to expected savings. The uncertainty of the model is a function of the variation in the modeled data, the amount of predicted savings during the post-retrofit period, and the duration of the measurement and verification period used to report the savings.
Fractional savings uncertainties, based on the electricity use model, are shown in Table 2. Uncertainties above the ASHRAE prescribed threshold of 50% are shown in red and should not be deemed as viable options for verifying energy savings.

**Table 2. Test Site A: Fractional Uncertainties in Electricity Savings**

<table>
<thead>
<tr>
<th>M&amp;V Period (months)</th>
<th>Predicted Savings</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
<th>25%</th>
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<tbody>
<tr>
<td>1</td>
<td></td>
<td>126.8%</td>
<td>63.4%</td>
<td>42.3%</td>
<td>31.7%</td>
<td>25.4%</td>
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<tr>
<td>2</td>
<td></td>
<td>89.6%</td>
<td>44.8%</td>
<td>29.9%</td>
<td>22.4%</td>
<td>17.9%</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>73.2%</td>
<td>36.6%</td>
<td>24.4%</td>
<td>18.3%</td>
<td>14.6%</td>
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<tr>
<td>4</td>
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<td>63.4%</td>
<td>31.7%</td>
<td>21.1%</td>
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<tr>
<td>5</td>
<td></td>
<td>56.7%</td>
<td>28.3%</td>
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<td>14.2%</td>
<td>11.3%</td>
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<tr>
<td>6</td>
<td></td>
<td>51.8%</td>
<td>25.9%</td>
<td>17.3%</td>
<td>12.9%</td>
<td>10.4%</td>
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<tr>
<td>7</td>
<td></td>
<td>47.9%</td>
<td>24.0%</td>
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<td>12.0%</td>
<td>9.6%</td>
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<td>8</td>
<td></td>
<td>44.8%</td>
<td>22.4%</td>
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<td>9.0%</td>
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<td>9</td>
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<td>42.3%</td>
<td>21.1%</td>
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<td>10</td>
<td></td>
<td>40.1%</td>
<td>20.0%</td>
<td>13.4%</td>
<td>10.0%</td>
<td>8.0%</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>38.2%</td>
<td>19.1%</td>
<td>12.7%</td>
<td>9.6%</td>
<td>7.6%</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>36.6%</td>
<td>18.3%</td>
<td>12.2%</td>
<td>9.1%</td>
<td>7.3%</td>
</tr>
</tbody>
</table>

Figure 5 represents a plot of the fractional savings uncertainties for electric demand (kW) at expected savings of 5%, 10%, 15%, 20% and 25%. The portions of each
curve that are below the 50% fractional uncertainty line indicate savings and M&V periods that would be suitable combinations for verifying expected savings.

**Figure 5. Test Site A: Fractional Uncertainties in Demand Savings**

Table 3 shows the fractional uncertainties represented in Figure 5. Unacceptable uncertainties – those above 50% -- are highlighted in red.

**Table 3. Test Site A: Fractional Uncertainties in Demand Savings**

<table>
<thead>
<tr>
<th>M&amp;V Period (months)</th>
<th>Predicted Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>1</td>
<td>242.3%</td>
</tr>
<tr>
<td>2</td>
<td>171.3%</td>
</tr>
<tr>
<td>3</td>
<td>139.9%</td>
</tr>
<tr>
<td>4</td>
<td>121.2%</td>
</tr>
<tr>
<td>5</td>
<td>108.4%</td>
</tr>
<tr>
<td>6</td>
<td>98.9%</td>
</tr>
<tr>
<td>7</td>
<td>91.6%</td>
</tr>
<tr>
<td>8</td>
<td>85.7%</td>
</tr>
<tr>
<td>9</td>
<td>80.8%</td>
</tr>
<tr>
<td>10</td>
<td>76.6%</td>
</tr>
<tr>
<td>11</td>
<td>73.1%</td>
</tr>
<tr>
<td>12</td>
<td>69.9%</td>
</tr>
</tbody>
</table>

Figure 6 shows a plot of the fractional savings uncertainty for natural gas usage at a confidence level of 68%. For example, at savings of 5% and an M&V period of 3 months, the fractional savings uncertainty is 370%. The maximum fractional
uncertainty allowed under ASHRAE Guideline 14-2002 is 50% of reported savings. Therefore, projected natural gas savings for energy measures resulting from faults identified by the FDD system, should exceed 20% if the maximum M&V period is eleven months.

**TABLE 4. TEST SITE A: FRACTIONAL UNCERTAINTY FOR NATURAL GAS SAVINGS**

<table>
<thead>
<tr>
<th>M&amp;V Period (months)</th>
<th>Predicted Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>1</td>
<td>641.9%</td>
</tr>
<tr>
<td>2</td>
<td>453.9%</td>
</tr>
<tr>
<td>3</td>
<td>370.6%</td>
</tr>
<tr>
<td>4</td>
<td>321.0%</td>
</tr>
<tr>
<td>5</td>
<td>287.1%</td>
</tr>
<tr>
<td>6</td>
<td>262.1%</td>
</tr>
<tr>
<td>7</td>
<td>242.6%</td>
</tr>
<tr>
<td>8</td>
<td>227.0%</td>
</tr>
<tr>
<td>9</td>
<td>214.0%</td>
</tr>
<tr>
<td>10</td>
<td>203.0%</td>
</tr>
<tr>
<td>11</td>
<td>193.6%</td>
</tr>
<tr>
<td>12</td>
<td>185.3%</td>
</tr>
</tbody>
</table>
**SYSTEM-LEVEL BASELINE**

The building is occupied primarily from 8 AM to 5 PM weekdays. The operations staff consists of three O&M contractors working the day shift who are tasked with maintaining occupant comfort, safety and performing preventative maintenance work.

**AIR-SIDE HVAC SYSTEMS**

The air distribution system is composed of five built-up, variable volume air handlers with chilled water coils for cooling. Three air handlers are located in the penthouse of the courthouse building and two air handling units (AHU) are located in the penthouse of the office building. Each AHU has vane axial supply and return fans with adjustable pitch blades to modulate airflow. All AHUs have full economizer capability and are equipped with low leakage opposed blade dampers. The schematic of a typical AHU is shown in Figure 7.

The AHUs supply conditioned air to three types of pressure independent variable air volume (VAV) boxes that serve individual zones throughout the facility. The three types of VAV boxes include: standard VAV, VAV with hot water reheat, and fan powered VAV with reheat.
**CHILLED WATER SYSTEM**

At the core of the chilled water plant are three chillers – two are 360 ton water-cooled, Trane centrifugal chillers with design peak load efficiency of 0.75 kW/ton and the third is a 80 ton reciprocating water cooled chiller. Chilled water distribution is a primary only constant flow system using three pumps. The chillers and pumps are located in the basement mechanical room. There are 2 chilled water pumps rated at 610 gpm and one rated at 121 gpm. The chilled water system was designed to operate at 45°F/55°F chilled water supply/return and 70°F/80°F condenser water supply/return. The lead chiller cycles based on outside air temperature, 5 days per week. Swapping of the lead and lag chillers is handled automatically through the on-site Building Automation System (BAS). All other chiller controls are done locally via the native control packages shipped with each chiller.

**BUILDING AUTOMATION SYSTEM**

The original Johnson Controls System installed in 1984 has been removed. The current BAS is a Delta Orca system installed in 2003. The Delta system is BACnet compatible and uses lined based (as opposed to graphical block) programming.

**TEST SITE B**

Test Site B is a commercial office building located in San Francisco, CA and operated by a 3rd party operations and maintenance contracting firm. Constructed in 1972, the 18 story building totals 420,000 square feet of conditioned space. Space types consist of open office areas with enclosed perimeter offices and conference rooms. Other areas include lobbies, corridors, kitchen and cafeteria, and a large data center on the 2nd floor. The building is occupied from 7:30 AM to 6 PM, Monday through Friday, with limited after hours and weekend use.

The building is built of steel frame construction with floor-to-ceiling dark tinted glass windows and spandrel with no exterior overhangs or other types of external window shading. Manually controlled Venetian blinds provide internal shading. A mechanical room in the penthouse covers a large percentage of the building rooftop, around which is a roof of built-up asphalt with bare concrete at the perimeter to accommodate window servicing equipment.

**WHOLE BUILDING BASELINE**

The baseline energy use summary for Test Site B is shown in Table 5. The period of available data for electricity is 9/1/2011 – 8/31/2010 and is the basis for the analysis presented in this section.
Table 5. Test Site B: Baseline Energy Use Summary

<table>
<thead>
<tr>
<th>Annual Electricity (per square foot)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumption</strong> 6,485,575 kWh/yr</td>
<td>15.4 kWh/ft²</td>
</tr>
<tr>
<td><strong>Maximum Demand</strong> 1,690 kW</td>
<td>4.01 W/ft²</td>
</tr>
<tr>
<td><strong>Cost</strong> 940,800 $/yr</td>
<td>2.2 $/ft²</td>
</tr>
<tr>
<td><strong>Cost/Unit</strong> 0.145 $/kWh</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Gas (Natural Gas) (per square foot)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumption</strong> 83,524 therms/yr</td>
<td>0.20 therms/ft²</td>
</tr>
<tr>
<td><strong>Gas Cost</strong> 57,656 $/yr</td>
<td>0.1 $/ft²</td>
</tr>
<tr>
<td><strong>Cost/Unit</strong> 0.69 $/therm</td>
<td></td>
</tr>
</tbody>
</table>

**Total Annual Energy Cost** 998,456 $/yr 2.37 $/ft²

Figure 8 shows monthly use and cost for electricity usage. Similar to Test Site A, monthly electricity use for is stable throughout the year.

Figure 9 shows the monthly electric demand profiles for the different time of use periods.
Monthly natural gas use and cost are shown for Test Site B are shown in Figure 10.

Figure 11 shows the fractional savings uncertainty as a function of M&V period for the baseline electricity model developed for the Test Site B. Fractional savings, from 5% to 25%, are well within the limits of ASHRAE Guideline 14-2002.
FIGURE 11. TEST SITE B: FRACTIONAL UNCERTAINTY IN ELECTRICITY SAVINGS

TABLE 6. TEST SITE B: FRACTIONAL UNCERTAINTY FOR ELECTRICITY SAVINGS

<table>
<thead>
<tr>
<th>M&amp;V Period (months)</th>
<th>Predicted Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>1</td>
<td>249.4%</td>
</tr>
<tr>
<td>2</td>
<td>176.4%</td>
</tr>
<tr>
<td>3</td>
<td>144.0%</td>
</tr>
<tr>
<td>4</td>
<td>124.7%</td>
</tr>
<tr>
<td>5</td>
<td>111.5%</td>
</tr>
<tr>
<td>6</td>
<td>101.8%</td>
</tr>
<tr>
<td>7</td>
<td>94.3%</td>
</tr>
<tr>
<td>8</td>
<td>88.2%</td>
</tr>
<tr>
<td>9</td>
<td>83.1%</td>
</tr>
<tr>
<td>10</td>
<td>78.9%</td>
</tr>
<tr>
<td>11</td>
<td>75.2%</td>
</tr>
<tr>
<td>12</td>
<td>72.0%</td>
</tr>
</tbody>
</table>
The baseline natural gas model for the Test Site B is shown in Figure 13. For an M&V period greater than 2 months and savings greater than 5%, the current model would be adequate for predicting annual savings.
**System-Level Baseline**

**Air-side HVAC Systems**

The air distributing system is single-duct variable air volume in most of the building with some constant volume package equipment serving computer rooms. Each floor from the 3rd floor to the 16th is served by one air handling unit delivering 24,000...
CFM to approximately 25 VAV boxes. Each air handling unit includes a cooling coil with an electronic two-way valve, a VFD controlled supply fan, pneumatically actuated return, outside and relief dampers and high efficiency air filters. The 17th floor and the 18th floors are served by a larger air handling unit common to both floors.

Each of the 271 VAV boxes serving the perimeter zones include a hot water reheat coil, while the 97 core zone VAV boxes are cooling only. The minimum air flow setting for the VAV boxes is one third of the maximum air flow, a turn down ratio of 33%.

CHILLED WATER SYSTEM

The cooling plant is located in the mechanical penthouse on the roof of the building. Chilled water is supplied by two 480 ton R-123 electric centrifugal chillers installed in 1997, (York Model YTJ3C3E2- CRH), with an efficiency of 0.70 kW/ton at full load, and include variable speed drives.

The chilled water distribution system is constant volume primary flow. The control valves at the air handling units are mostly two-way with three-way valves at the end of runs to maintain minimum flow. The chilled water pumps are split case, base-mounted, and driven by standard efficiency 50 HP motors. The pumps are piped in parallel, thus either pump can serve either chiller.

The building condenser water loop is served by two 575 nominal ton induced-draft cooling towers (Marley 8610 series). Each tower is single cell with one propeller fan driven by a standard efficiency single speed 20 HP fan motor, with ON/OFF control.

BUILDING AUTOMATION SYSTEM

The building’s central HVAC systems are controlled by an Automated Logic Controls (ALC) direct digital control (DDC) system that was installed in 1997. The DDC system provides occupied and unoccupied temperature control, optimum start, building-pressure control, duct-static control, cooling, heating, economizer, and VAV box control.

The building automation system (BAS) operates the HVAC system based on time of day schedule and load demand. The entire HVAC system is enabled at 6:00 AM and disabled at 6:00 PM, Monday through Friday. The fans start at 6:00 AM in a warm-up mode as follows: outside air dampers are closed, return dampers are fully open, VAV boxes are fully open, and reheat valves are open if outside air temperature (OAT) is below 65°F, return air is below 70°F, and space temperature is below set point.

At 7:30 AM, the warm-up mode ends and the air handling units operate to deliver discharge air temperature set point of 55°F. This set point is not automatically reset by the BAS and is an operator adjustable temperature. The supply fan speed modulates to maintain a supply duct static pressure set point of 1.2 inch water.

Air handling units control building static by opening relief dampers if space pressure increases above set point of 0.02” of water column. A demand control ventilation system measures CO2 levels in the return air stream and opens the outside air damper to 100% if the CO2 levels exceed the 1,000 parts per million (PPM).

If more than five (5) VAV boxes are calling for cooling, the air handling unit will be in cooling mode. If the air handler is in cooling mode and outside air temperature is below 75°F and more than 2°F below the return air temperature, then the
economizer dampers are open. If at least five (5) air handlers are calling for cooling and the outside air temperature is above 48°F, the chillers are enabled.

The boilers operate 24 hours per day, 7 days per week, if the pumps are running. The hot water pumps are enabled by building demand according to the number of zones that are calling for heating. A hot water three-way mixing valve modulates to provide discharge temperature set point of 175°F, by mixing the return hot water from the building with the hot water supply from the boiler, while maintaining constant flow through the boilers.

The night setback temperatures are 90°F for cooling and 60°F for heating, virtually disabling the system during unoccupied hours. Heat pump units are connected to the building automation system and are cycled to maintain space temperature set points, during occupied hours for the first floor lobby and the ninth floor cafeteria, and 24 hours per day in the computer labs throughout the building.

Computer room units are not connected to the BAS and operate based on their factory installed controls to maintain temperature and humidity set points as required in the computer room, 24 hours per day, and 365 days per year.

**FDD System Installation Summary**

Installation of the FDD system consists of five distinct stages of work – each carried out by representatives of the FDD vendor under the supervision of facility staff including the chief engineer, stationary engineers, controls engineers and IT staff.

1. Deploy the network-enabled hardware device at the facility
2. Integrate hardware device to recognize facility’s BAS control points
3. Connect the hardware device to a dedicated network
4. Configure the FDD system with the HVAC system and equipment control parameters
5. Monitor the output of the FDD system

**Hardware Deployment**

The FDD system utilizes a network-enabled hardware device to monitor the operation of the building automation system at the facility by connecting to the main branch of the BAS network. For each of the test sites, the hardware device supplied by the FDD vendor is a JENE-PC 1000 Controller which is capable of interfacing with other controllers that use communications protocols such as BACnet, LONworks and MODbus – as well as some proprietary protocols.

The device is installed at the facility and connected to the main branch of the BAS network via a standard Ethernet switch, as shown in Figure 14. The device also has a direct connection to the FDD vendor’s system (labeled as “FDD Supervisor”) which allows it to broadcast information to the remote FDD system for analysis. At each test site, deployment of this dedicated hardware was completed by employees of the FDD vendor.
Once the dedicated FDD hardware was deployed at each test site, a direct connection to the main BAS network was made via an existing Ethernet switch (shown as the purple connection in Figure). Using software preinstalled on the device, the hardware was configured by the FDD vendor to identify the other controllers on the network and the information that each is broadcasting and listening to.

A third connection is created between the FDD hardware installed at the facility and the FDD vendor’s remote network (shown as the blue dashed line in Figure 14). This is a DSL connection that connects both locations over the internet. In order to facilitate communication over internet protocol(s), the FDD hardware was assigned a static IP address, which allows information to be transmitted between the end points of the connection, specifically, between the FDD hardware at the facility and the servers located in the FDD vendor’s network.

The DSL connection is the transport mechanism used by the remote FDD system to periodically poll the FDD hardware device at the facility for new data. In addition to continuously collecting data from the BAS network, the FDD hardware device serves as a database that stores the information it collects.

Configuration of the FDD software is performed out of the purview of the FDD client; however, detailed information about the facility must be provided to FDD staff so that the software can be configured according to the unique HVAC systems that the system intends to monitor. The data gathering process includes:

**Hardware Integration with Building Automation System**

**Hardware Integration with External Network**

**FDD Software Configuration**
Collection of the following as-built documentation
- Mechanical schedules
- Building plans
- Test and balance reports

Documenting sequences of operation for all monitored systems by:
- Reviewing the existing BAS sequences of operation
- Interviewing controls engineers and/or contractors

Performing an initial scoping audit to document as-built HVAC systems, and control system details

FDD System Commissioning

Before the FDD system is available to the client, the FDD vendor conducts what they call a “Testing and Evaluation” phase. This step is needed in order to tune the faults and identify any issues that may have been overlooked during the configuration process. The commissioning process is a critical step and ensures that the system is not delivered to the client with inaccurate or misleading faults.

Costs

The FDD vendor’s pricing model is typically broken into two components: 1) an annual, recurring software-as-a-service “SaaS subscription” fee per SF, and 2) a one-time “Enablement” fee to deploy the software. The “SaaS subscription” fee assumes that prospect buildings are greater than 75,000 SF, have a BAS and that are direct digital controlled (“DDC”) or that are DDC-enabled, and fall within standard verticals such as commercial office, big box retail, hospitality, and industrial. The Enablement fee is determined by a) square footage of the building, along with b) BAS integration complexity, and c) metering and sub-metering needs depending on the facility.

Installation costs for each test site are summarized in the following sections. The realized costs are presented including software cost, DSL connections, IT hardware and any work needed from the control contractor enabling the integration.

Costs below provide rough cost approximations to the Vendor’s standard, but should not be taken as representative of all the Vendor’s fees and deployments, as this is in the context of varying technologies and a multi-party, utility-sponsored Pilot. A description of these changes are provided in

Test Site A

Realized installation costs for Test Site A are show in Table 9. The major component of the total cost is attributed to the subscription fee for the FDD system.
TABLE 9. TEST SITE A: REALIZED INSTALLATION COSTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Cost/Rate</th>
<th>Total</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year FDD Service Subscription ($0.19/ft²/yr)</td>
<td>269,337</td>
<td>$0.19</td>
<td>$51,174</td>
<td>96.4%</td>
</tr>
<tr>
<td>DSL Installation <em>(estimated)</em></td>
<td>1</td>
<td>$100</td>
<td>$100</td>
<td>0.2%</td>
</tr>
<tr>
<td>DSL Use per month <em>(estimated)</em></td>
<td>12</td>
<td>$50</td>
<td>$600</td>
<td>1.1%</td>
</tr>
<tr>
<td>Controls Contractor time for Installation</td>
<td>8</td>
<td>$150</td>
<td>$1,200</td>
<td>2.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>$53,074</td>
<td></td>
</tr>
</tbody>
</table>

TEST SITE B

Realized installation costs for the FDD system installed at Test Site B are shown in Table 10. Test Site B: Realized Installation Costs. An initial unrealized cost of $12,560 was required to alter the existing BAS in order to allow the FDD hardware to detect 12,560 legacy BACnet points.

TABLE 10. TEST SITE B: REALIZED INSTALLATION COSTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Cost/Rate</th>
<th>Total</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year FDD Service Subscription ($0.19/ft²/yr)</td>
<td>421,010</td>
<td>$0.19</td>
<td>$79,992</td>
<td>84.7%</td>
</tr>
<tr>
<td>DSL Installation <em>(estimated)</em></td>
<td>1</td>
<td>$100</td>
<td>$100</td>
<td>0.1%</td>
</tr>
<tr>
<td>DSL Use per month <em>(estimated)</em></td>
<td>12</td>
<td>$50</td>
<td>$600</td>
<td>0.6%</td>
</tr>
<tr>
<td>Controls Contractor</td>
<td>8</td>
<td>$150</td>
<td>$1,200</td>
<td>1.3%</td>
</tr>
<tr>
<td>Controls Contractor to make points BACnet compatible <em>(per control point)</em></td>
<td>1256</td>
<td>$10</td>
<td>$12,560</td>
<td>13.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>$94,452</td>
<td></td>
</tr>
</tbody>
</table>

LIST OF FAULTS WITH ANALYSIS

FAULT ANATOMY

Before discussing the list of faults identified by the FDD system at each test site, it is helpful to first outline the anatomy of a fault that is produced by the FDD software. This information has been garnished from reference material provided by the vendor for the purposes of this report.

Table 12 shows a list of each attribute and a corresponding description of what purpose the attribute serves. Additional information is identified including:

- Is the attribute updated by the system each time the fault is evaluated? (Fault Lifecycle Section)
- Can the attribute be changed by end users via the FDD web interface?
- Is the attribute visible via the web interface?
- Is the attribute visible in reports exported via the web interface?
TABLE 11. FAULT ATTRIBUTES

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
<th>Updated by System After Each Evaluation?</th>
<th>Can Be Changed By Users?</th>
<th>Visible In Web Interface?</th>
<th>Visible In Exported Reports?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault ID</td>
<td>A unique identifier for a fault instance. This is not shown in the user interface, but does appear in an exported fault report (in CSV format).</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Rank</td>
<td>An integer value from 1 (least severe) to 5 (most severe), that ranks the fault by cost and severity. The system assigns a rank value automatically and cannot be changed by end-users of the system.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Site</td>
<td>Indicates the location where the fault occurred. This is used for end-users monitoring multiple sites.</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Asset</td>
<td>An equipment ID of the system or piece of equipment where the fault was detected. This is generally the same equipment ID found in the facility’s equipment schedule.</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Status</td>
<td>An enumerated value indicating the resolution status of the fault. Observed values “Open” and “Closed.” It is not clear if other values exist.</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Description</td>
<td>A brief description of the fault which may or may not include dynamic data or control parameters that have been used in the fault logic.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Start Date</td>
<td>The first recorded occurrence of the fault instance.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of Occurrences (# Occ)</td>
<td>The number of times the fault has occurred since “Start Date”</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Minimum Time</td>
<td>The minimum duration the fault instance has been in the identified faulted condition, as explained in the fault description.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Maximum Time</td>
<td>The maximum duration the instance has been in the associated faulted condition, as explained in the fault description.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Total Time</td>
<td>The total cumulative time the fault has been in the associated faulted condition.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cost To Date</td>
<td>A calculated energy cost incurred for the fault based on “Total Time” based on a specific proprietary algorithm used to calculate the demand savings compared on an working system. A blended rate based on the site’s utility bills.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Priority</td>
<td>A selectable, enumerated value that allows end-users to change the priority of a fault. For some values, the “Rank” will be altered.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Owner</td>
<td>Not shown via the user interface, but included in exported fault reports</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**FAULT LIFECYCLE**

The lifecycle of a fault generated by the FDD system is, in some respects, unique to the vendor’s system. Fault instances are modeled as stateful objects and are operated on by both a time-dependent state machine within the vendor’s system and by end-users via the vendor’s web interface. Figure 15 represents a state transition...
diagram\(^3\) that illustrates the conceptual states of a fault and the actions that trigger transitions between each state.

A fault instance is created when the FDD system identifies that a condition, as defined by the associated fault type, has been met (transition 0-1). When the threshold value and the minimum fault duration threshold have been satisfied, the fault attributes are updated to the current state of the fault. The fault continues to be re-evaluated at an unspecified time interval\(^4\) – likely as new data is downloaded from the facility – and is updated each time the fault conditions are satisfied (transition 1-1). A fault instance will continue to be re-evaluated until it is closed either by an end-user via the FDD web-interface or by an FDD vendor administrator.

When a fault is closed by the user (transition 1-2) and hidden from view in the web-interface (state 2), it continues to be re-evaluated and may be re-opened (transition 2-1) if the fault condition is satisfied again. Faults can be deleted either by the user (transition 2-1-2), by being marked as “Resolved”, or by an FDD representative (transition 2-2-3). As part of their client support, the FDD vendor regularly reviews faults for validity and will remove faults (state 3) from the site that are deemed to be invalid (transition 2-3). Because these faults are removed from the site completely, the only way to communicate these changes to the client are through communications outside of the web application such as through email or by telephone. The FDD vendor recommends establish a communications protocol with their FDD vendor representative before using the FDD system.

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\(^{3}\) A state transition diagram is a way of describing the time-dependent behavior of a system. Circles are represented as states while arrowed-lines represent actions that are triggered by a condition. The start state is shown as a solid circle and end states are represented as double-lined circle. End states have no exiting transitions.

\(^{4}\) FDD vendor has confirmed that faults are re-evaluated every 5 minutes.
**FAULT COST CALCULATION**

In order to help users prioritize corrective action, the FDD system calculates the cost of wasted energy associated with a number of faults types. Specifically, these costs represent the cumulative value of energy that has been wasted due to a fault occurrence. These calculations are not intended to replace annualized cost saving estimates that are typical of energy cost/benefit analysis.

Costs are calculated on a five minute interval, aggregated in system’s database, and then displayed to the user if the total value is greater than $20. Although proprietary to the FDD software, the cost calculations are based on standard engineering equations that use actual point data and equipment attributes to calculate equipment energy consumption under both observed and “proper” operation.

**FAULT TYPE DEFINITIONS**

The FDD system deployed at each test site is currently configured to evaluate 23 individual fault types. They are loosely tied to specific systems and equipment types; however there are some faults that may apply to multiple systems. In the context of a generalized FDD system, the FDD vendor assigned name represents the fault while the description denotes the diagnostics component. For some fault type definitions, the text is parameterized with calculated or measured values that provide feedback.
to end-users that may be helpful to determine if the values have exceeded (or not) the associated fault condition.

The main component of a fault type is the function or equation used to determine if an asset has met the conditions required to signify that a fault has occurred. The fault condition is a function of several independent variables including:

- A proprietary equation defined by the FDD vendor that uses both measured time-series data points and additional operational parameters used by the BAS to control an asset as independent variables. The equation returns both a value of the fault being on/off, a time stamp and the duration of fault.
- A threshold condition used to determine if the equation result is either in a faulted state or not.
- A FDD vendor defined “Minimum Time” threshold.

Fault type groupings have been deduced empirically based on faults identified at each test site. Fault types are selected by the FDD staff during deployment and configuration and vary from site to site. Furthermore, the corresponding fault descriptions have been used to deduce the logic a given fault type uses to evaluate the condition of a system under consideration. It may be assumed that fault types are either still in active development, customized on a site-by-site basis, or part of the company’s proprietary intellectual property.

**General and Whole Building Faults**

Whole building faults typically identify the site name as the attributing “Asset” while general faults apply to a wide variety of the HVAC systems being analyzed. Most notably, outside air temperature sensors are affected by the “NOAA Temp Comparison” and “OAT Affected by Insolation” fault types. “Stuck Sensor” is a general fault typically applied to temperature and other environmental sensors used in typical HVAC control systems. Table 12 shows each of the faults that fall into these categories along with the descriptions presented to end-users via the FDD systems web-based user interface (UI).

Fault type descriptions with a value shown in brackets (e.g. “([reading]°F)”) indicate that the description is parameterized with a custom value derived from the fault condition.
**TABLE 12. GENERAL AND WHOLE BUILDING FAULTS**

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>User Interface Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA Temp Comparison</td>
<td>The outdoor air temperature measured by the sensor ([reading]°F) differs significantly from the temperature reported by the closest weather station ([reading]°F).</td>
</tr>
<tr>
<td>OAT Affected by Insolation</td>
<td>The outdoor air temperature measured by the sensor ([reading]°F) differs significantly from the temperature reported by the closest weather station ([reading]°F).</td>
</tr>
<tr>
<td>Stuck Sensor</td>
<td>The [sensor name] sensor value ([value]) has not changed.</td>
</tr>
</tbody>
</table>

**AIR-HANDLING UNIT FAULTS**

Fault types associated with Air-Handling Units (AHUs) are shown in Table 13. AHUs appear to have the most detailed fault and diagnostic coverage along with a total of 10 corresponding fault types. Fault type descriptions with a value shown in brackets (e.g. “([reading]°F)”) indicate that the description is parameterized with a custom value derived from the fault condition or input data.

The FDD vendor has indicated that “Operating Beyond Site Hrs”, “Operating unnecessarily” and “Program Schedule Check” should be classified as general faults.
<table>
<thead>
<tr>
<th>Fault Name</th>
<th>UI Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADU_DuctPressReset</td>
<td>The supply duct static pressure appears to have fixed setpoint [reading]</td>
</tr>
<tr>
<td>ADU_NoClgBufTempDrop</td>
<td>The supply air temperature [reading] is significantly lower than the mixed air temperature [reading] even though the unit is not calling for cooling.</td>
</tr>
<tr>
<td>ADU_OATDiffersFromMAT</td>
<td>The outside air damper is completely open, yet the outside air temperature differs from the mixed air temperature.</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADAtMinimumWhenAboveCO2Limit</td>
<td>The CO2 level is above the CO2 limit for Demand Controlled Ventilation (DCV), yet the outside air damper is still at minimum position.</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADNotAtMinimum</td>
<td>The CO2 level is below its limit and the outside air temperature is either greater than the return air temperature or the economizer high temperature lockout, yet the outside air damper is not at its minimum position.</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADNotFullyOpen</td>
<td>The outside air temperature is above the supply air temperature and below both the return air temperature and the economizer high temperature lockout, yet the outside air damper is not completely open.</td>
</tr>
<tr>
<td>ADU_UnneededMechanicalCooling</td>
<td>The outside air temperature is less than the supply air temperature setpoint, yet the unit is mechanically cooling.</td>
</tr>
<tr>
<td>Operating Beyond SiteHrs</td>
<td>This unit is operating outside of the user-defined business hours.</td>
</tr>
<tr>
<td>Operating unnecessarily</td>
<td>This asset is operating while unoccupied and within set point</td>
</tr>
<tr>
<td>Program Schedule Check</td>
<td>This unit is operating outside of the user-defined business hours.</td>
</tr>
</tbody>
</table>
**VARIABLE AIR VOLUME BOX FAULTS**

Table 14 shows the 8 fault types found to be associated with variable air volume (VAV) boxes. This includes both cooling-only and boxes with reheat; however heating related faults are not applied to cooling-only boxes. Fault type descriptions with a value shown in brackets (e.g. "([reading]°F)") indicate that the description is parameterized with a custom value derived from the fault condition.

**TABLE 14. VAV BOX FAULTS**

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>UI Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAV Heating When Parent Unit Off</td>
<td>The VAV box is calling for reheat even though the unit that provides air to the box is OFF.</td>
</tr>
<tr>
<td>VAV Insufficient Heating</td>
<td>The discharge air temperature ([reading]°F) has not risen above the supply air temperature ([reading]°F) despite a call for heating.</td>
</tr>
<tr>
<td>VAV_Costs_DATHigherThanSAT</td>
<td>The discharge air temperature ([reading]°F) has risen more than 5 degrees above the incoming air temperature ([reading]°F) even though reheat is not being called.</td>
</tr>
<tr>
<td>VAV_Costs_HeatingAboveMinimum</td>
<td>The unit is heating, yet the VAV airflow ([reading] cfm) exceeds the ventilation minimum ([design] cfm).</td>
</tr>
<tr>
<td>VAV_Costs_HeatSetpoint</td>
<td>The zone temperature, [reading], has not reached its setpoint, [reading], after an adequate amount of time.</td>
</tr>
<tr>
<td>VAV_Costs_MaxCFM</td>
<td>The VAV flow ([reading]) is more than 10% above the design flow maximum ([design]).</td>
</tr>
<tr>
<td>VAV_Costs_CoolSetpoint</td>
<td>VAV cooling below setpoint: The VAV is continuing to cool even though the setpoint, [setpoint value] is satisfied, [reading].</td>
</tr>
<tr>
<td>VAV_Costs_NoSetpointDeadband</td>
<td>The current difference between the heating and cooling setpoint ([reading]°F) is less than 3 degrees.</td>
</tr>
</tbody>
</table>
**CHILLED WATER SYSTEM FAULTS**

The 5 faults shown in Table 15 apply to chilled water systems. In some cases faults may apply to both the chilled water loop and the chilled water plant. Fault type descriptions with a value shown in brackets (e.g. "([readings]°F)") indicate that the description is parameterized with a custom value derived from the fault condition.

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>UI Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlr_StatusRunDisagreement</td>
<td>The chiller has been commanded off for some time yet there is still a drop from the return ([reading value]) to the supply ([reading value]), indicating that the chiller may be running.</td>
</tr>
<tr>
<td>CHW_Costs_Cool_NoFreeCooling</td>
<td>Waterside economizing is not occurring despite the supply water temperature ([reading]) being greater than outdoor air conditions ([reading]).</td>
</tr>
<tr>
<td>CHW_Costs_Cool_OperationBelowLockout</td>
<td>The chiller is running despite the outside air temperature ([reading]) being below lockout ([design]).</td>
</tr>
<tr>
<td>CHW_Costs_Off_CHWDelta</td>
<td>The difference ([calculated]) between the return and supply temperature on this chilled water loop is greater than ([design]), despite signs that the system is OFF.</td>
</tr>
<tr>
<td>CHW_GEN_ChillerCycling</td>
<td>The chiller was either enabled for a period less than 10 minutes, or was turned off for a period less than 10 minutes.</td>
</tr>
</tbody>
</table>

**FAULT REVIEW AND ASSESSMENT PROCESS**

The list of active faults reported by the FDD software at each test site were reviewed on a weekly basis by the engineering staff at each facility with the assistance of authors of this report, Test Engineers herein. The fault review and assessment process included the following steps:

1. Select faults instance by type based on the prioritization criteria defined by the chief engineer with input from the Test Engineers. Prioritization criteria includes:
   a. Wasted energy cost to date
   b. Importance of the associated system to the overall energy use of the building and to tenant comfort
   c. Existence of known issues with associated systems and equipment
   d. The quantity of faults associated with a given system or system type
2. Validate fault instance based on one or more of the following criteria:
a. Attribution to known issue

b. Trend review by chief engineer and Test Engineers

Once a fault was determined to be valid, Test Engineers reduced the faults into a collection of energy efficiency measures with analysis including:

1. Independent engineering calculations to determine the magnitude of estimated energy savings in terms of kWh, kW and therms
2. Calculated energy cost savings based on the pre-calculated blended cost of electricity incurred by the facility and the associated energy savings
3. Estimated implementation costs based on quotes provided by prospective contractors
4. Simple payback of each component of the project as well as the project as a whole

If a fault instance could not be verified or was found to be invalid, the FDD vendor was notified and the fault was removed from the FDD system.

**General, Whole Building and Chilled Water System Faults**

A limited number of these fault types were identified by the FDD system. Associated faults were therefore assessed individually by the chief engineer.

**AHU Faults**

AHU related faults were initially assessed jointly by the chief engineer and Test Engineers. Faults were prioritized using the following criteria.

1. Quantity of faults associated with a given AHU
2. Total cost of wasted energy
3. Existence of known issues

**VAV Faults**

The VAV faults required a more thorough assessment process due to both the large number of faults and the number of VAV boxes. Additionally, due to limitations placed on accessing the equipment during normal work hours, the process was formalized with input from the chief engineer. The process worked as follows:

1. **[Chief Engineer]** Assign a list of VAV faults (by floor) for inspection
   a. This may include noting the MAX airflow as compared to design specifications
2. **[Stationary Engineer]** Inspect each faulted VAV according to fault description (there may be multiple faults)
   a. Record the results of inspection in Notes Section
      i. Notes should contain
         1. Original MAX CFM (if different)
         2. Result of Inspection should be one of the following:
            a. [Fault Verified]
            b. [Fault Invalid] include justification
c. [Unsure] include questions or points of clarification needed to resolve
   b. Submit comment and assign to Test Engineer
      i. DO NOT Check ‘Resolve’ checkbox
   c. Do not fix anything, as trivial as it may seem because it will prevent customer from getting an incentive from the utility
   d. Notify Chief Engineer when all VAVs in assigned list have been commented and assigned to Curtis

3. **[Test Engineer]** Run report and merge fault comments into report spreadsheet
   a. Setup meeting with Chief Engineer to review list of investigated faults
   b. Roll verified faults into the current MBCx energy efficiency project to claim incentive
      i. Assume fixes will be covered by current operating budget
      ii. Depending on proposed fix, some metering may be necessary
      iii. Baseline VAVs that will be fixed based on BAS trends or standalone loggers
   c. Assign unverified or false-positive faults to FDD vendor representative

**FAULT ANALYSIS**

**Test Site A**

Table 16 shows a compiled list of faults identified by the FDD system. The faults span the period of 1/25/2012 to 5/28/2012. It should be noted that the high number of “Stuck Sensor” and “VAV_Cost_CoolSetpoint” faults may be attributed to the issue discussed later in Lessons Learned. Specifically, connectivity to the site has been lost and it is assumed the fault logic is evaluating stale data, or in the case of “VAV_Cost_CoolSetpoint”, data that is all zeros.
Further analysis of the faults at Test Site A are still ongoing, but have been delayed due to the still outstanding connectivity issue (see Lessons Learned for more details).

A total of the energy costs attributed to each fault type are shown in Table 17 for each system type under investigation. The FDD system has identified a total of $66.38 in wasted energy costs for the period of 1/25/2012 to 5/28/2012. 38.9% of the total cost is associated with economizer operation issues ("ADU_OADNotFullyOpen"), while the rest are associated with VAV box overheating. The total wasted energy reported by the system is 0.034% of the facility’s baseline energy cost.
A compiled list of faults span the time period of 3/10/2012 to 9/7/2012. The system has identified a total of 352 faults during this time. “Stuck Sensor” and “VAV_Costs_MaxCFM” account for 43% of all faults.
Results from the ongoing AHU fault assessments are shown in Table 19. Of the 103 individual faults investigated, 17 were determined to be valid because of a known issue. Description of the known issue is provided in a later section describing the energy efficiency and demand savings model for Test Site B.
<table>
<thead>
<tr>
<th>Fault Type</th>
<th>AHU</th>
<th>VAV</th>
<th>Whole Building</th>
<th>Chilled Water System</th>
<th>Total</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADU_DuctPressReset</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_NoCigButTempDrop</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_OATDiffersFromMAT</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADAtMinimumWhenAboveCO2Limit</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADNotAtMinimum</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADNotFullyOpen</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_UnneededMechanicalCooling</td>
<td>$777.18</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$777.18</td>
<td>100.0%</td>
</tr>
<tr>
<td>Chlr_StatusRunDisagreement</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>CHW_Costs_Off_CHWDelta</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>CHW_GEN_ChillerCycling</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>NOAA Temp Comparison</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>OAT Affected by Insolation</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Operating Beyond SiteHrs</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Operating unnecessarily</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Program schedule check</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Sensors Didn't Fall</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Stuck Sensor</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV Heating When Parent Unit Off</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV Insufficient Heating</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV_Costs_DATHigherThanSAT</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV_Costs_HeatingAboveMinimum</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV_Costs_MaxCFM</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Totals</td>
<td>$777.18</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$777.18</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 20. AHU FAULT ASSESSMENT RESULTS

<table>
<thead>
<tr>
<th>Fault Investigation Status</th>
<th>Total</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Logic Too Sensitive</td>
<td>8</td>
<td>7%</td>
</tr>
<tr>
<td>Fault Uses Inaccurate Proxy Point</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Fault Uses Incorrect Operating Schedule</td>
<td>1</td>
<td>0%</td>
</tr>
<tr>
<td>Fault Uses Nonexistent Point</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Fault Evaluated Outside of Asset Operating Schedule</td>
<td>1</td>
<td>2%</td>
</tr>
<tr>
<td>Fault Evaluating Non-Existing Control Sequence</td>
<td>5</td>
<td>4%</td>
</tr>
<tr>
<td>Fault Invalid: FDD Vendor Adjusted Operating Schedule</td>
<td>15</td>
<td>13%</td>
</tr>
<tr>
<td>Fault Invalid: System Operating Within Scheduled Time</td>
<td>1</td>
<td>4%</td>
</tr>
<tr>
<td>Fault Logic Duplicates Other Fault Type</td>
<td>5</td>
<td>6%</td>
</tr>
<tr>
<td>Unable to Validate Fault</td>
<td>3</td>
<td>3%</td>
</tr>
<tr>
<td>Fault Invalid: Assigned to FDD Vendor for Adjustment</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Not Investigated: No Energy Savings Possible</td>
<td>9</td>
<td>8%</td>
</tr>
<tr>
<td>Not Investigated Yet</td>
<td>7</td>
<td>11%</td>
</tr>
<tr>
<td>Fault Uses References Unknown Point</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Fault Valid: Known Issue</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Fault Attributed To Known Issue</td>
<td>17</td>
<td>15%</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>16 9 2 18 19 17 16 5 3 115</td>
</tr>
</tbody>
</table>

General observations for each fault type are as follows:

- **ADU_DuctPressReset**: This fault is not part of the current sequence of operation for AHUs at the facility.

- **ADU_NoClgButTempDrop**: This fault condition is met by most AHUs in the evening hours when the HVAC systems are not running. Temperature differentials between the supply air and mix air temperatures are generally no greater than ±5°F. This fault type should be less sensitive and should only run while the AHUs are in operation.

- **ADU_RelDBEcon_OADAtMinimumWhenAboveCO2Limit**: Fixing this issue will not result in energy savings and was therefore not included in the fault assessment. This fault, however, does identify a possible indoor air quality issue when CO2 levels are high yet the air handler is still ventilating with a minimum amount of outside air.

- **ADU_RelDBEcon_OADNotAtMinimum**: This fault has not been investigated due to overlapping logic with similar fault types.

- **ADU_RelDBEcon_OADNotFullyOpen**: For the majority of AHUs at the facility, the mixed air and economizer dampers are linked to the same actuator. The
economizer dampers are reverse acting. The BAS does not have a control point associated with the economizer damper position; the fault logic appears to be using the mix air damper position as a proxy point. This approach assumes that the mixed air damper position is the reciprocal of the economizer (100% outside air damper) position which may not be the case mechanically where one damper has a longer stroke length than another.

- **ADU_UnneededMechanicalCooling**: This is another fault that uses an incorrect proxy point. The fault logic appears to use the valve position at the cooling coil; however, the valve may be open even when the chiller plant is off. A more accurate approach may be to use the chilled water supply temperature and/or plant status and valve position to determine if the unit is cooling.

- **ADU_OATDiffersFromMAT**: In all but two of the AHUs, there is a return air plenum leak. During periods when an AHU with this problem is in economizer mode, return air is leaked into the mixed air plenum, which would cause the mixed air to be warmer than outside air. Therefore, this fault not only identified the air handler leakage, but also corroborated the engineering staff’s knowledge of this issue through data analysis.

- **Operating Beyond Site Hrs**: All but one of these faults have been fixed when an FDD representative re-configured the operating hours used by the underlying fault logic. AHU-1 is still being faulted because it runs 24/7 to supply ventilation to the lobby. It appears the fault logic for this fault type uses the same schedule for all AHUs and is not capable of evaluating different operating schedules.

- **Operating unnecessarily**: This fault appears to duplicate the fault logic for “Operating Beyond Site Hrs,” as well as “Program Schedule Check.”

- **Program Schedule Check**: This fault appears to be a duplicate of “Operating Beyond Site Hrs”, as well as “Operating unnecessarily.” Interestingly, it has the same fault type description as “Operating Beyond Site Hrs” but the same number of faults as “Operating unnecessarily.”

- **Stuck Sensor**: One fault duplicates the ‘ADU_DuctPressureReset’ check and references the static pressure sensor, which doesn’t change. One fault is attributed to a known issue on the 9th floor where the CO₂ sensor has been disabled because of infiltration from the kitchen. The last fault has not been investigated yet because of the sensitivity of the 17th floor which houses executive offices.

Fault assessment results for VAV boxes are shown in Table 21. 46% of the total VAV faults generated by the FDD system were not validated. 14% are currently under investigation by an on-site stationary engineer and 40% have not been investigated.
A total of three issues have been identified for Whole Building type faults. Two faults, “NOAA Temp Comparison” reference the building’s outside air temperatures sensors. A third fault, “OAT Affected by Insolation”, references one of the sensors, but it is not known which one.

The building has two outside air temperature (OAT) sensors: a primary sensor located on the roof and a secondary sensor located on the 10th floor. The FDD system indicated that the OAT sensor readings are different from readings provided by a local NOAA station. The details of the fault logic and station readings are not known, so two standalone temperature loggers were launched at the site to verify the fault condition.

Figure 16 shows a comparison of the BAS sensor readings, data collected by the loggers and an additional weather source (weatherunderground.com). The logger installed on the 10th floor was placed at the outside air intake of AHU-10, near the secondary sensor. Discrepancies between the 10th Floor logger readings and the 10th floor BAS sensor are likely caused by the return air plenum leak described above.
A common method for determining the accuracy of an OAT sensor is to plot the sensor readings for a given period against readings made by a secondary source. Figure 16 shows a plot of the BAS OAT sensor readings (vertical axis) against readings made by the standalone logger (horizontal axis). The optimal condition (shown in red) shows the range where both readings are exactly the same. If the two sensor readings matched, all points (blue) would be shown on the red line. The temperature difference between the blue points and the red line are used to compute the standard deviation of BAS temperature readings compared to those of the standalone logger.

The difference between the BAS OAT sensor readings and the standalone logger has a standard deviation of 1.7 °F – an accuracy of approximately 2% for readings between 55 and 90 °F. This is well within the range of accuracy of typical OAT sensors and indicates that the BAS sensor readings are sufficiently accurate.
The nearest NOAA weather station is approximately 2 miles from the facility. It has been determined that the fault logic may be too sensitive. A larger dead-band should be used to account for any potential errors caused by the difference in proximity of the facility and the nearest NOAA station. A better approach may be to use a third calibrated temperature sensor connected directly to the on-site data collection hardware as a reference or calibrate the site's sensor as part of the installation.

Assessment results for faults created by the FDD system for the facility’s chilled water system are shown in Table 22. Nine of the sixteen faults have been deleted by the FDD vendor as a result of false positives generated when the system lost connectivity (see Lessons Learned). One of the “CHW_GEN_ChillerCycling” faults, referencing a pony chiller, was found to be invalid because the ‘Start Date’ and ‘End Date’ of the fault occurred when the chiller was not running. This may also be an invalid proxy point issue in the fault logic; however, the point used to determine chiller cycling is not known. Another 5 faults have not been investigated yet.
TABLE 22. CHILLED WATER SYSTEM FAULT ASSESSMENT RESULTS

<table>
<thead>
<tr>
<th>Fault Investigation Status</th>
<th>Chlr StatusRunDisagreement</th>
<th>CHW_Costs_Off CHWDelta</th>
<th>Operating Beyond SiteHrs</th>
<th>Sensors Didn't Fail</th>
<th>Stuck Sensor</th>
<th>Program schedule check</th>
<th>Total</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unable to Validate Fault</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Fault Deleted By FDD Vendor</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Not Investigated Yet</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Duplicate Fault</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>1</td>
<td>16</td>
</tr>
</tbody>
</table>

The cumulative energy costs generated by the FDD system to date are shown in Table 23. Cost breakdowns for each system are shown in each column along with a total cost by fault type and the percentage of total cost. A total of $777.18 is attributed to “ADU_UnneededMechanicalCooling”. The total fault cost is 0.08% of the baseline energy costs for Test Site B.

TABLE 23. TEST SITE B: FAULT COST TOTALS BY SYSTEM

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>AHU</th>
<th>VAV</th>
<th>Whole Building</th>
<th>Chilled Water System</th>
<th>Total</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADU_DuctPressReset</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_NoClgButTempDrop</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_OATDiffsFromMAT</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OAD4MinWhenAboveCO2Limit</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADNot4Minimum</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_RelDBEcon_OADNotFullyOpen</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>ADU_UnneededMechanicalCooling</td>
<td>$777.18</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$777.18</td>
<td>100.0%</td>
</tr>
<tr>
<td>Chlr StatusRunDisagreement</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>CHW_Costs_Off CHWDelta</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>CHW_GEN_ChillerCycling</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>NOAA Temp Comparison</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>OAT Affected by Insolation</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>Operating Beyond SiteHrs</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>Operating unnecessarily</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>Program schedule check</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>Sensors Didn’t Fail</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>Stuck Sensor</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV Heating When Parent Unit Off</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV Insufficient Heating</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV_Costs_DATHigherThanSAT</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV_Costs_HeatingAboveMinimum</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>VAV_Costs_MaxCFM</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>0.0%</td>
</tr>
<tr>
<td>Totals</td>
<td>$777.18</td>
<td>$ -</td>
<td>$ -</td>
<td>$ -</td>
<td>$777.18</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
ENERGY EFFICIENCY AND DEMAND SAVINGS MODEL

An energy efficiency and demand savings model, using the collection of faults and associated systems included in this study, are difficult to express because of the limited sample size of validated faults at each test site. Other standardized methodologies, such as comparison of current building performance to established benchmarks, such as those taken from the Commercial Building Energy Consumption Survey (CBECS), may proved to be a more effective approach for determining the energy savings potential for typical HVAC systems. Additionally, simplified simulation tools for commercial buildings, such as the Building Optimization and Analysis (BOA) Tool\textsuperscript{5}, offer standardized approaches for calculating energy savings for common energy efficiency measures.

Alternatively, it may be beneficial to present the energy efficiency measures that have been identified as a result of the ongoing fault investigation and discuss the findings in the context of this FDD study. This information is helpful to demonstrate how the issues generated from an automated fault detection and diagnostics tool are distilled into an energy efficiency project.


test site a

The identified energy efficiency measures are shown in Table 24. The energy measure directly related to faults discovered is EEM 7 to calibrate VAV boxes and normalize set points. The other measures were identified outside of the FDD software. The incentives are based on the utility incentive provided by PG&E’s Monitoring Based Commissioning (MBCx) program. The customer was has instituted a request for proposals in order to secure an installation budget for 2013. The total energy savings for these measures account for 18\% of the electricity and 7\% of natural gas use.

\textsuperscript{5} The BOA tool is an Excel spreadsheet-based tool to streamline and standardize energy savings calculations. It distributed by the California Collaborative and developed by the major investor owned utilities in California (PG&E, SCE, SDG&E, SMUD)

### TABLE 24. ESTIMATED ENERGY EFFICIENCY MEASURE RESULTS SITE A

<table>
<thead>
<tr>
<th>Measure Description</th>
<th>Annual Savings kWh/yr</th>
<th>Peak Demand Reduction kW</th>
<th>Annual Savings therms/yr</th>
<th>Energy Cost Savings $/yr</th>
<th>Measure Cost $/yr</th>
<th>Estimated Incentive $/yr</th>
<th>Simple Payback years</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEM 1 Recode schedule on exhaust fans to run based on occupancy</td>
<td>5,400</td>
<td>0.0</td>
<td>0</td>
<td>$744</td>
<td>$1,500</td>
<td>$486</td>
<td>1.4</td>
</tr>
<tr>
<td>EEM 2 Install VFD to control garage exhaust fan with CO sensors</td>
<td>34,600</td>
<td>0.0</td>
<td>0</td>
<td>$4,768</td>
<td>$22,000</td>
<td>$3,114</td>
<td>4.0</td>
</tr>
<tr>
<td>EEM 3 Recode lighting schedule to tighten lighting operating schedule</td>
<td>94,700</td>
<td>0.0</td>
<td>0</td>
<td>$13,050</td>
<td>$2,900</td>
<td>$4,735</td>
<td>Immediate</td>
</tr>
<tr>
<td>EEM 4 Convert from constant to variable flow for chilled water pumping system</td>
<td>31,600</td>
<td>0.0</td>
<td>0</td>
<td>$4,354</td>
<td>$52,300</td>
<td>$2,844</td>
<td>11.4</td>
</tr>
<tr>
<td>EEM 5 Replace chillers with high efficiency VFD chillers</td>
<td>88,800</td>
<td>48.3</td>
<td>0</td>
<td>$12,237</td>
<td>$615,000</td>
<td>$18,150</td>
<td>48.8</td>
</tr>
<tr>
<td>EEM 6 Install new boiler to replace the existing boiler</td>
<td>0</td>
<td>0.0</td>
<td>400</td>
<td>$400</td>
<td>$50,800</td>
<td>$400</td>
<td>126.0</td>
</tr>
<tr>
<td>EEM 7 Calibrate VAV boxes and standardize VAV box setpoints</td>
<td>30,300</td>
<td>0.0</td>
<td>1,300</td>
<td>$5,475</td>
<td>$47,900</td>
<td>$4,027</td>
<td>8.0</td>
</tr>
<tr>
<td>EEM 8 Install a 71 kW PV cells on the roof of the Courthouse</td>
<td>103,000</td>
<td>71.0</td>
<td>0</td>
<td>$14,193</td>
<td>$497,500</td>
<td>$133,900</td>
<td>25.6</td>
</tr>
<tr>
<td>EEM 9 Install energy meters on major HVAC equipment</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>$0</td>
<td>$112,300</td>
<td>$0</td>
<td>N/A</td>
</tr>
<tr>
<td>EEM 10 Optimize existing sequence of operations</td>
<td>123,300</td>
<td>0.0</td>
<td>500</td>
<td>$17,491</td>
<td>$74,600</td>
<td>$11,597</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>511,700</td>
<td>119.3</td>
<td>2,200</td>
<td><strong>$72,700</strong></td>
<td><strong>$1,476,800</strong></td>
<td><strong>$179,300</strong></td>
<td>17.8</td>
</tr>
<tr>
<td><strong>Total less EEM 8 PV and EEM 9Meters</strong></td>
<td>408,700</td>
<td>48</td>
<td>2,200</td>
<td><strong>$58,507</strong></td>
<td><strong>$867,000</strong></td>
<td><strong>$45,400</strong></td>
<td>14.0</td>
</tr>
</tbody>
</table>

#### Test Site B

The identified energy efficiency measures are shown in Table 25. Energy savings have been estimated with the BOA Tool and are based on the key attributes of the building and systems each measure affects. The incentives are based on the utility incentive provided by PG&E’s Monitoring Based Commissioning (MBCx) program.
The fault “ADU_DuctPressureReset” fault was used to validate EEM 1, in addition to a review of the sequence of operation for each AHU. Measure cost is based on a quote provided by the facility’s controls contractor. Identification of EEM 2 is based on feedback from the chief engineer and other facility staff. It is assumed that the “ADU_OATDiffersFromMAT” fault may be an indicator of this issue and that by implementing this measure, the associated fault will stop being flagged as an issue by the FDD system. The implementation cost is based on a quote from the facility’s primary mechanical contractor. EEM 3 was identified by the FDD system via the “Stuck Sensor” fault. This measure does not have any associated energy efficiency savings.

Overall the customer was interested in using this information as a proposal in order to secure an operations and maintenance budget for the next fiscal year. At this time, the customer has not committed to implementing these measures. The total energy savings for these measures account for less than 1% of the facility’s baseline use.

**Calculation Methodology for EEM 2**

The savings estimate for EEM 2 at Test Site B are based on the average of a conservative estimate and an estimate based on ideal integrated air-side economizer operation.

**Conservative Energy Savings Estimates**

Conservative savings estimates are based on a proposed condition that includes an additional fan heat of 3°F added to the supply air. It is assumed that under normal operating conditions the air-side economizer will operate in full economizer mode for OAT between 55°F and 72°F. Operating hours of the economizer include weekdays from 6 AM to 6 PM or 1550 hours/year.

Energy savings are based on the difference between baseline conditions and proposed conditions.

\[
\text{Annual Energy Savings (kWh)} = \left[ \text{Baseline Demand} \times \text{Hours} \right] - \left[ \text{Proposed Demand} \times \text{Hours} \right]
\]

Baseline conditions are calculated as follows:

\[
\text{Baseline Demand (kW)} = 1.08 \times \text{CFM} \times \text{SFPD} \times \frac{(\text{MAT} - \text{SATSP})}{\text{COP} \times 3413}
\]
Proposed conditions are calculated as follows:

\[
\text{Proposed Demand (kW)} = 1.08 \times \text{CFM} \times \text{SFPD} \times \frac{(\text{OAT} + 3 - \text{SATSP})}{\text{COP} \times 3413}
\]

**Table 26. Savings Estimates Using Conservative Proposed Conditions**

<table>
<thead>
<tr>
<th></th>
<th>Annual Savings (kW)</th>
<th>Annual Energy Cost Savings</th>
<th>Implementation Cost</th>
<th>Incentive</th>
<th>Simple Payback (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU-02</td>
<td>2056</td>
<td>$298</td>
<td>$4,037</td>
<td>$185</td>
<td>12.9</td>
</tr>
<tr>
<td>AHU-03</td>
<td>1561</td>
<td>$226</td>
<td>$4,037</td>
<td>$140</td>
<td>17.2</td>
</tr>
<tr>
<td>AHU-04</td>
<td>1060</td>
<td>$154</td>
<td>$4,037</td>
<td>$95</td>
<td>25.6</td>
</tr>
<tr>
<td>AHU-05</td>
<td>2637</td>
<td>$382</td>
<td>$4,037</td>
<td>$237</td>
<td>9.9</td>
</tr>
<tr>
<td>AHU-06</td>
<td>3402</td>
<td>$493</td>
<td>$4,037</td>
<td>$306</td>
<td>7.6</td>
</tr>
<tr>
<td>AHU-07</td>
<td>2636</td>
<td>$382</td>
<td>$4,037</td>
<td>$237</td>
<td>9.9</td>
</tr>
<tr>
<td>AHU-08</td>
<td>2049</td>
<td>$297</td>
<td>$4,037</td>
<td>$184</td>
<td>13.0</td>
</tr>
<tr>
<td>AHU-09</td>
<td>0</td>
<td>$0</td>
<td>$4,037</td>
<td>$0</td>
<td>-</td>
</tr>
<tr>
<td>AHU-10</td>
<td>1990</td>
<td>$288</td>
<td>$4,037</td>
<td>$179</td>
<td>13.4</td>
</tr>
<tr>
<td>AHU-11</td>
<td>4158</td>
<td>$603</td>
<td>$4,037</td>
<td>$374</td>
<td>6.1</td>
</tr>
<tr>
<td>AHU-12</td>
<td>3223</td>
<td>$467</td>
<td>$4,037</td>
<td>$290</td>
<td>8.0</td>
</tr>
<tr>
<td>AHU-13</td>
<td>3262</td>
<td>$473</td>
<td>$4,037</td>
<td>$294</td>
<td>7.9</td>
</tr>
<tr>
<td>AHU-14</td>
<td>1947</td>
<td>$282</td>
<td>$4,037</td>
<td>$175</td>
<td>13.7</td>
</tr>
<tr>
<td>AHU-15</td>
<td>1686</td>
<td>$244</td>
<td>$4,037</td>
<td>$152</td>
<td>15.9</td>
</tr>
<tr>
<td>AHU-16</td>
<td>0</td>
<td>$0</td>
<td>$4,037</td>
<td>$0</td>
<td>-</td>
</tr>
<tr>
<td>AHU-17</td>
<td>1479</td>
<td>$214</td>
<td>$4,037</td>
<td>$133</td>
<td>18.2</td>
</tr>
<tr>
<td>AHU-18</td>
<td>2602</td>
<td>$377</td>
<td>$4,037</td>
<td>$234</td>
<td>10.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>35750</td>
<td>$5,184</td>
<td>$68,633</td>
<td>$3,217</td>
<td>12.6</td>
</tr>
</tbody>
</table>

There are no savings for AHU-09 and AHU-16, based on the conservative proposed conditions.
**Energy Savings Estimates Based on Ideal Conditions**

Energy savings estimates are based on a proposed condition that assumes MAT will track OAT exactly with no fan heat included. It is assumed that under normal operating conditions the air-side economizer will operate in full economizer mode for OAT between 55°F and 72°F. Operating hours of the economizer include weekdays from 6 AM to 6 PM or 1550 hours/year.

Energy savings are based on the difference between baseline conditions and proposed conditions.

\[ \text{Annual Energy Savings (kWh)} = [\text{Baseline Demand} \times \text{Hours}] - [\text{Proposed Demand} \times \text{Hours}] \]

Baseline conditions are calculated as follows:

\[ \text{Baseline Demand (kW)} = 1.08 \times \text{CFM} \times \text{SFPD} \times \frac{(\text{MAT} - \text{SATSP})}{\text{COP} \times 3413} \]

Proposed conditions are calculated as follows:

\[ \text{Proposed Demand (kW)} = 1.08 \times \text{CFM} \times \text{SFPD} \times \frac{(\text{OAT} - \text{SATSP})}{\text{COP} \times 3413} \]
While conservative estimates indicate AHU-09 and AHU-16 will not provide energy savings, using ideal conditions indicates that these units will have energy savings. This may indicate that these units are currently operating at or near the conservative conditions; MAT follows OAT + 3 across all OAT conditions between 55°F and 72°F.
ANALYSIS METHODOLOGY

To analyze the savings potential of air-side economizers, baseline data has been collected from March 2012 to Nov 2012 at 15 minute intervals. Data for the following points have been collected for each air handler:

- OAT
- MAT
- SAT
- SATSP

The data represented in the charts below has been filtered based on the following conditions:

- At least one chiller is running
- The AHU cooling coil valve is open
- The AHU supply fan is running

Three charts are produced to demonstrate the operation of each economizer. The first chart shows MAT, SAT and SATSP versus OAT. Figure 20 and Figure 21 are examples. Figure 20 represents GOOD economizer operation because MAT (red) is very close to the line showing Ideal (purple) operation – where MAT closely follows OAT across all temperatures. Figure 21 shows POOR economizer operation – where MAT is well above the Ideal line of demarcation and diverges from ideal to a greater extent.
degree of magnitude at lower OATs. Other items of interest indicate that both AHUs represented in the charts are using SAT reset.

The second plot shows only MAT versus OAT and includes a line of best fit to indicate the average MAT along all OAT readings. An orange circle shows the area where the MAT deviates from the ideal conditions and the OAT range where energy savings can be achieved if the economizer operation is improved.
The last chart shows the modeled MAT (red), proposed conservative condition (blue) and proposed ideal condition for the economizer (green). The model provides the basis for the annual savings calculation.

**FIGURE 24. EXAMPLE BASELINE MODEL AND PROPOSED**
PROBLEM FINDER SPECIFICATION FOR CANDIDATE HVAC SYSTEMS

A problem finder specification is presented for the fault detection and diagnostics of air-side and water-side systems. The specification targets potential PG&E product launches.

SPECIFICATION

The goal of this specification is to outline the technical and functional requirements of a problem finder tool. The objectives of this tool are as follows:

1. Provide commercial facilities a simplified methodology to identify common problems with the following HVAC systems:
   a. Variable Air Volume Boxes
   b. Air-side Economizers
   c. Air Handlers
   d. Chilled Water Systems

2. Provide building operators with a simplified approach for the direct translation of faults into existing utility funded energy efficiency programs by utilizing existing energy efficiency measure calculation tools.

3. Establish a two-tier incentive framework that gives building operators an initial low-barrier incentive to identify and fix issues and provide them further recourse for additional incentives based on the successful measurement and verification (M&V) of the resulting savings.

PROBLEM FINDER TOOL REQUIREMENTS

1. A Problem Finder Tool shall be composed of a collection of Excel workbooks, developed specifically for identifying supported issue types.

2. Issue types shall have a one-to-one relationship with measures supported by the current version of the Building Optimization and Analysis (BOA) Tool. Measures included:
   a. AHU Schedule
   b. Economizer
   c. Zone Temp Deadband
   d. Supply Air Temperature Reset
   e. Duct Static Pressure Reduction
   f. Duct Static Pressure Reset
   g. Supply Fan VFD
   h. Boiler Lockout
   i. Chilled Water Supply Temperature Reset
   j. Chilled Water Pump VFD
   k. Lighting Schedule
   l. Lighting Occupancy Sensor
3. A issue type finder tool shall be developed as a single worksheet in the Problem Finder Tool workbook

4. A issue type worksheet shall include the following static content:
   a. The standardized name of the issue type
   b. A description of the issue type
   c. A technical explanation of how the issue type is determined
   d. A description of how to use the worksheet
   e. A matrix of symptoms that may indicate an issue exists along with instructions for determining how to perform preliminary validation of the problem
   f. A matrix of system types and configurations that the issue applies to. This shall be similar to how the BOA Tool identifies supported measures for the various HVAC systems and control approaches.

5. A issue type worksheet shall include the following pre-developed functionality:
   a. An equation to be applied to the user-inputs that returns a TRUE or FALSE value that indicates if the issue type was identified in the data input
   b. When applicable, a status field for each row that returns a TRUE or FALSE value that indicates if the issue type was identified for the corresponding data

6. A issue type worksheet shall have the following inputs:
   a. A user-selectable inputs to indicate:
      i. Unique equipment schedule ID of equipment or system under review
      ii. Key design parameters of equipment. This is defined by the inputs required by the corresponding measure defined in the BOA Tool
   b. A matrix for trend data to be collected via the BAS, including:
      i. A timestamp column
      ii. One or more value or status columns
      iii. A list of user selectable inputs above each value or status column to indicate:
         1. Controller and Point ID where data was collected
         2. Measurement units of trended data

7. A issue type worksheet shall have the following outputs
   a. A status field (TRUE or FALSE) to indicate if the associated issue has been identified in the trended data entered by the user
   b. A status field (TRUE or FALSE) to indicate if errors were detected in the trend data

**USE OF THE PROBLEM FINDER TOOL**

1. The Problem Finder Tool shall be straight forward to understand and use by semi-technical operations personnel who are familiar with operating the on-site BAS

2. When a building operator believes a system is faulty or behaving outside of expected conditions, the operator shall consult the issues defined in the Problem Finder Tool.
3. Based on feedback from the Problem Finder Tool, the operator will be instructed to enter the required data into the issue worksheet corresponding to the assumed problem. This may include, equipment data and control parameters (e.g. set points, dead-bands, equipment specifications, schedules) and trend data retrieved from the BAS.

4. In the event that the operator is unable to complete the issue worksheet, a 3rd party consultant may assist with the completion of the worksheet.

5. If a completed issue worksheet has validated the issue based on the entered information, the information shall be used to fill out the corresponding measure worksheet in the BOA Tool to indicate the proposed post-installation conditions and corresponding energy savings.

**PROPOSED TERMS AND CONDITIONS**

1. Facility managers choosing to participate in the Problem Finder Tool program shall be provided the services of a 3rd party consultant for assistance.

2. The 3rd party consultant shall assist the facility with vetting issues, filling out the Problem Finder Tool and BOA Tool, and helping facility personnel with related tasks.

3. Program participants shall receive a portion of the future program incentive (TBD) for the completion of the Problem Finder Tool and BOA Tools for any issues identified at the facility using the tool.

4. The program incentive shall be based on the measured savings, as determined after the measures have been implemented; however, the initial incentive paid to the participant will be based on the savings estimated by the BOA Tool.

5. The program participant shall have the option to implement the measures identified in the Problem Finder Tool. By not implementing the measures, the customer agrees to not seek further incentives from the program until the measures have been successfully implemented and verified by a 3rd party energy consultant under direction of the program administrator.

6. After successful measurement and verification of the measure savings, the program participant will receive the remainder of the incentive (based on the verified savings), minus the initial portion paid.

7. Measurement and verification of each measure shall be carried out by a 3rd party energy consultant under the direction of the program administrator. The baseline conditions will be based on the original data entered into the Problem Finder Tool. The post-installation conditions will be retrieved from the BAS using the data supplied in the submitted Problem Finder and BOA Tools.
**FAULT DETECTION AND DIAGNOSTICS TOOL SPECIFICATION**

A generalized fault detection and diagnostic tool specification is presented using lessons learned thus far from this study. The purpose of this specification is to standardize the use of FDD tools as a means for identifying common HVAC issues that will help commercial facilities improve energy efficiency and reduce electric demand. Furthermore, a secondary objective is to ensure that candidate FDD tools focus primarily on issues related to energy efficiency and assist facility and energy managers with translating issues into attainable energy savings.

**FDD SOLUTION**

1. An Fault Detection and Diagnostics solution ("Product") shall be considered a software or hardware product that is capable of identifying common issues relating the operation of HVAC system and include capability to evaluate lighting scheduling issues.
2. A Product shall provide feedback to end-users as to the cause of issues it identifies and shall include suggestive measures to help validate, troubleshoot and/or fix the problem.
3. The types of issues identified by the Product shall have a one-to-one mapping to the Energy Efficiency Measures supported by the energy efficiency program.
4. The Product shall be well documented and address, at a minimum, the following material:
   a. A list of the individual faults generated by the Product
   b. Technical information that documents the engineering methodology used for each fault type
   c. Example engineering calculations that demonstrate how each fault type operates
   d. A list of the systems, equipment and control sequences supported by each fault
   e. A system schematic including how the Product integrates with typical building automation systems
   f. A list of the supported building automation systems and communications protocols

**ROLES AND RESPONSIBILITIES**

1. FDD Product Vendors ("Vendors") shall provide all the documentation and system requirements for Product
2. Vendor shall be responsible for the successful installation, configuration and commissioning of their Product.
3. Vendor shall provide customers with all Product documentation before installation.
4. Vendor shall provide on-site training to customers after Product is installed.
5. Vendor shall be responsible for the prompt resolution of any issues related to the installation, configuration and commissioning of the Product.
6. Vendor support services shall be included in the initial cost of the Product to ensure the ongoing health and accuracy of Product.
7. Users of the Product (“Users”) are people that interact with the system using the user interface. Users may include facility managers, operations staff or energy consultants.

**Performance Criteria**

1. Customers will enter into contract with Vendor based on the performance of the FDD tool.
2. Performance of the FDD tool shall be based on the ratio of false-positives to actual faults and the quantity of actual faults identified. This shall ensure that the FDD tool is not creating more work than the potential it has to help save energy.
3. Faults should be evaluated, at a minimum, on a daily basis. Shorter interval evaluations may add to the responsiveness of the system and allow Users to identify issues for critical high availability systems like those for datacenters, research or medical applications.

**Functional Requirements**

**Fault Anatomy and Behavior**

1. A fault type definition shall be composed of the following properties:
   - A parameterized function that returns a Boolean value which shall be used to indicate the status of a fault condition
     - Underlying function shall be clearly documented in Product documentation
     - Arguments shall be strongly typed indicating the data type and clearly documented in Product documentation
   - A well documented description describing the intent of the fault
2. A fault instance identified by Product shall be enumerated with the following attributes:
   - Unique identifier (ID)
   - Fault type that references the Product documentation
   - System or equipment ID that references the facilities equipment schedule
   - Priority value represented as an integer. Default should be zero.
   - A status field indicating if the fault is muted
   - A timestamp field indicating the date when the fault should be un-muted
3. A fault instance shall have the following references:
   - A list of the control points used in the evaluation of the fault condition and referenced in the fault type function list of parameters in order
A list of timestamps indicating each time the fault condition was determined to be true
- An audit trail that maintains a history of changes to the attributes of a fault instance including the ID of any user-initiated interactions

**Key User Interactions**

1. **Muting a fault instance**
   a. Users shall have the ability to “mute” a fault. Muting a fault instance causes the fault to be assigned the lowest priority (zero). Faults are muted by changing the mute status of a field to TRUE and assigning the date when the fault should be un-muted. This feature allows users to silence a fault that is caused by a known issue such as a system that is being repaired.

2. **Prioritizing a fault instance**
   a. Users shall have the ability to assign a priority to a fault. Prioritizing faults allows users to filter a list of faults based on this assigned rank. This value may be changed periodically based on a user-defined prioritization rule set.

3. **Prioritizing a fault type**
   a. Users shall have the ability to assign a priority to a fault type. This is similar to prioritizing a fault instance; however, the priority is assigned to all fault instances of the corresponding type.

4. **Prioritizing equipment or systems**
   a. Users shall have the ability to assign a priority to equipment or systems. Again, this is similar to fault prioritization and will allow users to filter a group of faults based on the indicated rank.

5. **Add comment to a fault**
   a. Users shall have the ability to add comments to a fault. Comments shall be persisted as part of the fault history and should be displayed in the fault detail view.

6. **Mass assignment of fault attributes**
   a. Users shall have the ability to change the properties of a group of faults at one time, such as muting, prioritizing or commenting.

7. **Ad Hoc Fault Evaluation**
   a. Users shall have the ability to force the evaluation of a fault. This allows faults to be investigated at unscheduled intervals. Additionally, it will allow users to modify the attributes of a fault and determine if the modifications had an effect on the fault condition.

**Reporting Interface**

1. Faults shall be displayed in a tabular format listing each fault attribute
2. Systems and equipment shall be listed in a tabular format listing each attribute used by the fault function.
3. Fault types should be displayed in a tabular format with a corresponding list of systems and equipment evaluated by each type.

4. All objects displayed in tabular format shall be sort-able and filterable by attribute.

5. The following graphical components shall be displayed when viewing an individual fault instance:
   a. A list of comments in chronologic order
   b. A list of the changes to the fault attributes shown in chronological order
   c. A time series graph indicating each time and duration the fault condition is evaluated to be true
   d. A table of values showing:
      i. Average fault duration
      ii. Average hour of day when fault condition is true
      iii. Number of occurrences when fault condition is true

**Workflow and Fault Management**

1. Product shall have simplified workflow management features which allow users to actively track, investigate and resolve faults.

2. Fault instance shall have the following workflow attributes
   a. Owner ID: The User ID of the person assigned to the fault
   b. Investigation Status: An enumerated list with the following options:
      i. New (default)
      ii. Under Investigation
      iii. Invalid
      iv. Valid
      v. Fault Corrected
   c. Investigation Date: The last date the investigation status was changed

3. Users shall have the ability to change the workflow attributes

4. Tabular fault list shall be sort-able and filterable by workflow attributes

5. When the Investigation Status for a fault instance is changed the system shall prompt the User to enter a comment and assign the fault to another User (such as the chief engineer or facility manager)

- The Reporting Interface shall allow users to email and export fault lists to other users. This allows faults to be included in communications or analysis outside of the FDD system.

**Lessons Learned**

A collection of key take-aways is presented regarding installation and customer acceptance of the FDD system. Items are organized into groups and discussed in further detail within each subsection.
COMPATIBILITY WITH BAS PROTOCOLS

At Test Sites B, the FDD hardware device was incompatible with nearly half of the legacy Delta Orca controllers used at the facility. As a result, additional costs of approximately 15% of the total project cost was required to have a controls contractor create BACnet compatible proxy points for the FDD system to use.

At Test Site C, the FDD hardware device was incompatible with all of the Automated Logic Corp. (ALC) controllers installed at the facility. Based on an initial cost estimate provided by the controls contractor, the site was dropped from the study.

CONNECTIVITY WITH HARDWARE DEVICE

At both of the ongoing test sites, Test Sites A and B, connectivity between the FDD hardware device and the vendor’s remote network has been disrupted. At Test Site A, a network breach resulted in the FDD device being disconnected and the DSL line blocked from receiving incoming connections. At Test Site B, two unscheduled disruptions have occurred, each lasting approximately a week or more.

The connectivity issue at Test Site A is as yet unresolved due to changing IT security requirements with the building owner. It is not clear if the FDD vendor will be able to restore the connection, thus allowing for further analysis of the initial collection of faults identified at the facility.

A side effect of the connectivity issue occurs when the FDD system does not receive new data. It appears that the system continues to re-evaluate the faults with no data which in turn causes a large number of incorrect faults to be created. For example all the AHUs and VAVs get faulted with the “Stuck Sensor” fault as the logic sees that the data point hasn’t changed over time. These false positives are shown to end-users via the web interface and the quantity of faults increases dramatically. In one such case the number of faults when from 256 to over 2,000 fault overnight. As a result, the FDD vendor implemented new data protocols to recognize lost connectivity and prevent misidentification of “Stuck Sensor” faults.

Lastly, the hardware device at Test Site B was relocated three times. The first relocation was due to the cable length issues which exceeded the maximum run length (300 feet) for Gigabit Ethernet connections. Subsequent moves were initiated by the on-site IT department to improve connectivity with the local network and random access point (RAP) used to connect the hardware with the external DSL line. Working through these issues delayed configuration and commissioning of the FDD system by several weeks due to coordination and planning of the additional IT resources.

See Future FDD Product Enhancements for a response from the FDD vendor regarding this issue.

CONFIGURATION AND COMMISSIONING OF FDD SOFTWARE

The configuration process which entails translating all of the operational and design parameters that exist in the BAS into a useable configuration for the FDD system is a complex and often error prone endeavor. This configuration is used to establish a benchmark for the optimal operation of the building and allows the FDD system to determine if the building systems are operating outside of the expected conditions.
LARGE NUMBER OF FALSE-POSITIVES

Any errors or incorrect assumptions made by the vendor during the configuration phase are likely to result in false positives – faults that indicate a specific issue exists when in actuality the fault logic has misinterpreted the data. False-positives degrade a client’s confidence in the FDD system.

More importantly, the time required to investigate false-positives results in wasted time and labor costs. For example, the time required to investigate the outside air temperature fault.

FDD SYSTEM CONFIGURATION IS SLOW TO EVOLVE WITH CHANGES TO BAS

As changes are made to the BAS as part of the normal operation of the building, the configuration of the FDD system must change accordingly. For example, Test Site B is in the process of implementing tenant improvements on some of the floors. As such, engineering staff have manually disabled points for this floor via the BAS. This causes the trended data sent to the FDD system to include stale data for the corresponding points which results in a large number of invalid faults.

The current version of the FDD system does not allow end-users of the FDD system to make adjustments to the system configuration. Clients must rely on representatives of the FDD vendor to change settings that, if left unchanged, are likely to result in inaccurate fault assessments. While end-users are able to close individual faults, in turn removing them from the dashboard, this practice diminishes confidence in the accuracy and reliability of the faults. Furthermore, end-users may want to adjust the sensitivity of the fault condition for some equipment. Allowing this type of ad hoc tuning may improve the effectiveness of a fault or fault type and allow building operators to determine the severity of a fault.

FAULTS ARE REMOVED FROM THE SYSTEM WHEN SYSTEM IS RE-COMMISSIONED

After the system was deployed and commissioned at a facility, the FDD system required regular tuning by the vendor based on feedback from the operations and maintenance staff. These continuous improvements caused a large number of faults to disappear from the system which causes the number of faults to fluctuate dramatically. Furthermore, for users who are using the total number of faults to gage the quality or performance of the facility’s HVAC systems, a drastic reduction in faults may be misleading or cause new faults to be overlooked.

It may be beneficial to have a better feedback mechanism for any manual or large scale changes made to a facility’s FDD system configuration. For example, instead of hiding closed faults from the system dashboard, faults might be labeled with a different status that would allow end-users to relate a fault to any irregular changes made by representatives of the FDD vendor.

USABILITY OF FDD SYSTEMS AND USER INTERFACE

The FDD vendor has indicated that the current state of their system and web application interface is undergoing continuous improvements. These issues may or may not be applicable in future versions, but are included in this report to comply with the contract obligations of this study.
FDD Website Compatibility With Older Browsers

The chief engineer’s primary workstation at Test Site B still used Internet Explorer version 7. The FDD dashboard does not render correctly in older browsers and key features of the web site including those used for filtering faults by asset were not useable. An example screenshot of this is problem is shown in . As a work-around, the chief engineer worked with his company’s IT support person to install an alternate browser.

Fault Costs are Expressed as Cumulative Sum

The cumulative cost of each fault instance is expressed as a sum of the product of number of occurrences, the total time the fault was in a faulted condition and the unit cost of energy. Energy savings are typically expressed as monthly or yearly savings, so as to assist facility managers with determining avoided cost and any potential utility incentives associated with fixing the problem.

Workflow Management

The chief engineer at Test Site A expressed frustration with the usability of the FDD web application. Most importantly, the application does not provide an easy way for clients to manage workflow – the collaboration and user-application interactions required to track the progress of ongoing fault investigations and resolutions. This is especially a problem at scale or when a large number of faults and systems are investigated in parallel. For example, when a given fault type is validated for one system, there may be other similar systems in the building. In order for the chief engineer to find anomalies between faults and systems, and thus reduce the labor costs of each fault, he or she must address each fault individually and enter a separate comment into the system for each fault.

As a workaround, it was found that exporting all faults into a CSV format and using a spreadsheet tool to track each fault was a more effective approach. Unfortunately
this approach caused a disconnect between the information entered into the spreadsheet and any changes that occurred to the list of fault since the last export.

**Transparency of FDD System Internals**

The proprietary nature of the FDD system results in a lack of transparency of how the FDD system functions. While FDD vendor representatives continue to provide ongoing support, use of the system includes a steep learning curve for some building operators that do not have a technical engineering background. The issues identified in this section cite a lack of system documentation; however, this may not be the fault of the FDD vendor as the intent of their services may be designed to bridge the gap between the operation of their system and the specific client needs. The issues below may be a bi-product of the irregular client roles introduced by this research project.

**No Documentation of Fault Logic**

The logic used by each fault type, to assess the fault state of an asset, is not available in any of the FDD system documentation – nor is it available in the FDD web application aside from the fault type description displayed for each fault. This creates confusion for end-users tasked with investigating the cause of each fault. For simple faults, such as ‘Stuck Sensor’, this issue does not cause unneeded complexity; however, for more complicated faults that target systems with a large number of interactive effects, the process of pinpointing the fault cause is at times challenging.

**No Documentation of Fault Cost**

The total fault cost calculation is not documented and not annualized. Fault cost is one of the key metrics commonly used to determine if fixing an issue is cost effective. Facility managers typically evaluate this cost in conjunction with other criteria to determine the overall budget for energy efficiency measures.

**No Documentation of Which Faults Types are Applied to Each Asset**

As a part of the configuration and commissioning process, the FDD vendor does not provide a comprehensive list of which fault types are analyzed for each asset. Users of the system must deduce this information from the list of generated faults.

**Validation and Diagnostics are Difficult Due to Lack of Fault Detail**

The diagnostic component of the vendor’s FDD solution, which users review to determine the cause of or potential fix for a given fault, is limited in scope. While the system provides some information in the body of the fault description, it is not always apparent which control points are used to determine the condition of the fault. To validate the cause of a fault, building operators use the facility’s BAS as a window in the behavior of the system and compare their findings with the details of the fault presented in the FDD user interface. Control points are typically referenced by the controller and point ID (or name) displayed in the BAS management interface. Because the FDD system does not use native BAS point names in the fault detail, building operators must assume that the system is using the correct point. In a large number of fault instances, especially those associated with VAV boxes and AHUs, the incorrect controller point was mapped to the logic of the fault type. Arriving at this
conclusion came from the feedback of a FDD vendor representative and would have been less time consuming had the control point been referenced as part of the fault detail information.

Because faults are re-evaluated on a regular basis, the FDD system records the initial date ("Start Date") when the fault was detected. As a fault continues to exist, the FDD system updates the number of occurrences and last date ("End Date") the fault was detected. When investigating a fault, having only two data points indicating when the fault was detected often limits how effectively the reviewer can inspect the trend history of the affected systems. Furthermore, it prevents the reviewer from detecting recurring anomalies that help pinpoint the cause of the fault. For example, it would be helpful to understand if a fault is occurring at regular intervals or during a particular time of day.

shows an example of how a large number of faults may be visually analyzed using the time of day that fault types occur. The horizontal axis shows the average hour of day for the "Start Date" attribute of each fault type, for each system group. "VAV Heating When Parent Unit Off" appears to happen at 2:30 AM. It has been determined that the logic for this fault is not correct because it may be using the wrong point, likely hot water valve position, to determine if the unit is heating. After investigating faults of this type, it is apparent that even though the valve is open, the hot water plant and pumps are off.

FIGURE 26. AVERAGE START TIME BY FAULT TYPE
CUSTOMER ACCEPTANCE

Customer engagement at Test Site A has been challenging. As a property managed by a large governmental organization, it is difficult to approach operations and maintenance staff with additional work that is beyond the scope of their contractual obligations. During the course of this research project, the chief engineer changed. As a result, it has been difficult to bring the new chief up to speed on the project and engage him to help investigate the collection of initial faults.

The operations and maintenance staff at Test Site B have shown interest in actively using the FDD system. The chief engineer has actively reviewed faults and helped verify and invalidate issues relating to the list of identified faults; however, usability of the FDD System, as discussed in Lessons Learned, has been a major hurdle. Specifically, the chief engineer is intent on investigating major faults, but has been discouraged by both the additional effort required to manage the process tracking faults and by the number of false positives encountered for the initial set of faults identified by the system.

TRANSLATING FAULTS INTO ENERGY SAVINGS

While several of the fault types provide direct mappings to common energy efficiency measures, other fault types can be difficult to isolate and used to translate fixing the issue into an energy savings opportunity. Furthermore, it may be difficult for building operations staff to identify which faults, aside from their operational implications, may be suitable candidates for targeting when establishing a budget to fix them. For example the “ADU_DuctPressReset” is a common fault that clearly translates to an energy measure to reset duct static pressure in most energy efficiency programs. Scheduling related fault types (“Operating Beyond SiteHrs” and “Operating unnecessarily”) are also well supported measures. On the other hand, “Stuck Sensor” the AHU related fault types are challenging to disaggregate when considering the interactive effects of the fault or when system has more than two faults.

Energy savings is not typically the primary design intent of most FDD systems. Rather, fault detection is often associated with preventative maintenance and providing building operators with automated feedback of building systems. Energy savings, in many cases, is a by-product of a FDD system functions.

The assumed intent of the FDD vendor’s business model is to help bridge this gap and provide the technical support to customers that will help them interpret and formulate an action plan for the faults at their facility. This again, may not have been given adequate attention due to the roles and responsibilities employed in this research effort.

FAULT PRIORITIZATION AT SCALE

The FDD system currently has two features which may help customer’s prioritize the level to which faults are investigated and fixed. The cumulative cost attribute of a fault instance is the primary method used to assess the severity of faults. When the cost attribute is not populated, end-users can also use the FDD assigned “Rank” value to assess the severity of a fault.

There may be other factors that help a facility manager determine the severity of a fault; however, this requires the diligence of the manager to review the details of each fault and either assign the fault a priority, by manually changing the “Priority”
attribute of each fault instance, or adding a comment to the fault. At scale, this ongoing management is time consuming.

For a large number of faults, the process of assigning a priority to each fault is labor intensive using the FDD interface. Furthermore, building operators may have additional prioritization criteria they use to assess the severity of faults. This may include giving priority to systems with a large energy footprint (e.g. chillers, air handlers, systems that run continuously, etc.) or addressing faults for systems that have high importance such as executive offices or areas with known issues.

The flexibility of the FDD system to accommodate and adapt to the prioritization criteria adopted by the operations staff is limited and therefore results in additional work to actively manage the evolving collection of active faults. A simple approach may be to allow end-users the ability to assign a priority factor to assets or fault types which would allow the system to automatically rank faults based on the user defined criteria.

**Future FDD Product Enhancements**

This section contains a list of future enhancements to the FDD product, as reported by the FDD vendor.

**Connectivity Issues**

The FDD vendor has provided a response to the hardware connectivity issues encountered during this research effort. Their responses are as follows:

- FDD vendor no longer produces stuck sensor faults when connection is lost. Diagnostics automatically stop running and the FDD vendor manager of the account is automatically notified of the issue.
- FDD vendor has invested in more expertise in the expert services group. The new management has a controls integration background and will insure that gateway devices installations are robust.
- FDD vendor now maintains ongoing service contracts with local controls providers to ensure that, if outages do occur, it is the controls companies contractual responsibility to restore communication in a timely fashion.

**On-boarding Options**

FDD vendor representatives have reported that in the future their system will have a standard point naming convention and standard XML format that they can provide to customer and controls contactors who wish to send trend data to the FDD vendor once every 24 hours via an [FDD vendor] hosted FTP site. For site who’s IT will not allow a DSL line or any other form or remote access to the FDD hardware gateway, FDD vendor can configure the hardware and export XML files. This means that there is one-way outbound communication from the site, using FTP, which is authorized in most IT security scenarios.
**System Compatibility**

It is important to note that in addition to BACnet, the FDD hardware is also compatible with LONwork and MODbus, as well as some proprietary systems. Non-compatible systems can pursue the direct XML export option described above.

**Product Costs**

The FDD vendor reports that the initial product cost is the sum of two components: the annual subscription and an enablement fee for installing and configuring the system. Per the FDD vendor’s input, enablement is a flat fee in the sense that it is a onetime fee. However, it is determined by square footage along with BAS integration, and metering and sub-metering depending on the facility and prospect.
Appendices

Test Site B Air-Side Economizer Plots

AHU-02

Figure 27. AHU-02 Measured Data
FIGURE 28. AHU-02 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 29. AHU-02 BASELINE MODEL AND PROPOSED
AHU-03

Figure 30. AHU-03 Measured Data
FIGURE 31. AHU-03 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
Figure 32. AHU-03 Baseline Model and Proposed
AHU-04

FIGURE 33. AHU-04 MEASURED DATA
FIGURE 34. AHU-04 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 35. AHU-04 BASELINE MODEL AND PROPOSED
AHU-05

**FIGURE 36. AHU-05 MEASURED DATA**

![Graph showing AHU-05 measured data with different data points and lines representing various conditions.](image-url)
FIGURE 37. AHU-05 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 38. AHU-05 BASELINE MODEL AND PROPOSED
AHU-06

FIGURE 39. AHU-06 MEASURED DATA
FIGURE 40. AHU-06 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 41. AHU-06 BASELINE MODEL AND PROPOSED
AHU-07

FIGURE 42. AHU-07 MEASURED DATA
Figure 43. AHU-07 Mixed Air Temperature vs. Outside Air Temperature
AHU-08

FIGURE 45. AHU-08 MEASURED DATA
FIGURE 46. AHU-08 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 47. AHU-08 BASELINE MODEL AND PROPOSED
FIGURE 48. AHU-09 MEASURED DATA
FIGURE 49. AHU-09 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 50. AHU-09 BASELINE MODEL AND PROPOSED
AHU-10

FIGURE 51. AHU-10 MEASURED DATA
FIGURE 52. AHU-10 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 53. AHU-10 BASELINE MODEL AND PROPOSED
AHU-11

FIGURE 54. AHU-11 MEASURED DATA
FIGURE 55. AHU-11 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 56. AHU-11 BASELINE MODEL AND PROPOSED
AHU-12

FIGURE 57. AHU-12 MEASURED DATA
FIGURE 58. AHU-12 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
Figure 59. AHU-12 Baseline Model and Proposed
AHU-13

FIGURE 60. AHU-13 MEASURED DATA
FIGURE 61. AHU-13 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
Figure 62. AHU-13 Baseline Model and Proposed
AHU-14

Figure 63. AHU-14 Measured Data
FIGURE 64. AHU-14 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 65. AHU-14 BASELINE MODEL AND PROPOSED
AHU-15

FIGURE 66. AHU-15 MEASURED DATA

- MAT
- SAT
- SATSP
- Ideal
FIGURE 67. AHU-15 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
Figure 68. AHU-15 Baseline Model and Proposed
AHU-16

FIGURE 69. AHU-16 MEASURED DATA
Figure 70. AHU-16 Mixed Air Temperature vs. Outside Air Temperature
FIGURE 71. AHU-16 BASELINE MODEL AND PROPOSED
AHU-17

FIGURE 72. AHU-17 MEASURED DATA
FIGURE 73. AHU-17 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 74. AHU-17 BASELINE MODEL AND PROPOSED
AHU-18

FIGURE 75. AHU-18 MEASURED DATA
FIGURE 76. AHU-18 MIXED AIR TEMPERATURE VS. OUTSIDE AIR TEMPERATURE
FIGURE 77. AHU-18 BASELINE MODEL AND PROPOSED