Enterprise Plug-N-Play Diagnostics and Optimization for Smart Buildings

FINAL PROJECT REPORT

ENTERPRISE PLUG-N-PLAY DIAGNOSTICS AND OPTIMIZATION FOR SMART BUILDINGS

Prepared for: California Energy Commission
Prepared by: Ezenics, Inc.

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DISCLAIMER

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation
- *Enterprise Plug-N-Play Diagnostics and Optimization for Smart Buildings* is the final report for the Enterprise Plug-N-Play Diagnostics and Optimization for Smart Buildings project (contract number 500-08-050) conducted by Ezenics, Inc. (formerly Sensus MI). The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The goal of this project was to develop, deploy, and evaluate low-cost, plug-n-play, enterprise fault detection and diagnostics solutions for heating, ventilation, and air conditioning and refrigeration systems to reduce energy consumption and increase occupant comfort.

Research in both the academic and private sector has shown that there are many existing problems in commercial buildings that can be solved by ensuring that existing equipment and controls are working as intended, rather than through large capital expenditures. The New Building Institute 2004 report *"Review of Recent Commercial Rooftop Unit Field Studies in the Pacific Northwest and California"* is one example of such evidence.

Onsite commissioning has shown success in identifying such operational problems and has gained momentum with support from utilities and the industry. Opportunities for improvement are that it is often a costly onsite analysis at a single point in time. Automated fault detection continuously checks the incoming data with fault algorithms that have been tuned to the specific site, all while eliminating costly onsite visists. The Ezenics fault detection system was rapidly deployed in over 33,000,000 square feet of retail space across California to demonstrate that high net value is achievable through a plug-n-play, automated fault detection platform, which is robust, low cost, and scalable.

A cloud based data exchange carrier was used to store data for all of the building systems. To compensate for missing sensors and the inability to take on site measurements, five virtual sensors were created. Then, the appropriate algorithms were deployed and an independent contractor tested the results to ensure accuracy in the full rollout to 252 locations. The data exchange carrier collects a total of 555,200 data points continuously from 16,480 machines encompassing multiple systems and external data sources. The fault diagnostics identified 27,754 issues for an annual calculated savings of $3,790,096.

Keywords: California Energy Commission, detection and diagnostics, FDD, Ezenics, Target, HVAC, principle component analysis, automated fault detenction and diagnostics, near-zero-cost, non-invasive, enterprise plug-n-play diagnostics and optimization

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EXECUTIVE SUMMARY

Throughout the country, in both public institutions, such as universities, and private businesses research has been performed that provides evidence that there are many existing problems in commercial buildings that can be solved by ensuring existing equipment and controls are working as intended as opposed to the large capital expenditures needed to replace the equipment. The New Building Institute report *"Review of Recent Commercial Rooftop Unit Field Studies in the Pacific Northwest and California"* (Cowan, 2004) is one example providing such evidence. It is not uncommon to hear of facilities with award-winning energy efficient design and construction that are later found to be operating inefficiently.

On-site commissioning has proved to show success in identifying such operational problems and has gained some momentum with support from utility companies and the industry. Opportunities for improvement surrounding traditional commissioning are that it is often a costly on-site analysis at a single point in time. To ensure persistence, traditional commissioning needs to be done at least annually and even more often to be somewhat continuous, that can affect the return on investment. Additional work is then required to ensure that found issues are actually resolved.

The California Energy Public Interest Energy Research sponsored Plug-n-Play Diagnostics and Optimization for Smart Buildings project goals have been to develop and demonstrate that low-cost and quickly deployable multi-system diagnostic technology can more effectively scale the benefits of commissioning, and fault detection and diagnostics. This project will facilitate faster adoption of the technology, facilitating financial and carbon reduction savings from large opportunity commercial buildings.

The goals of this project were to develop, demonstrate, deploy, and evaluate near-zero-cost, non-invasive, plug-n-play diagnostics and optimization technologies that could be adopted by both existing and new buildings immediately. The objectives were to:

1. Develop a data exchange carrier on a scalable infrastructure that establishes connectivity with an unlimited number of building automation systems to obtain, calibrate, store, and process data at a near-zero-cost manner.
2. Develop five low-cost virtual sensors that expands the onboard measurements and enable existing and new diagnostics and optimization technologies.
3. Develop multiple-system based diagnostics and optimization technologies that address the interactions among different systems of the same type and different types of systems in buildings.
4. Integrate existing and new technologies into an enterprise plug-n-play diagnostics and optimization solution for enabling smart buildings, to deploy in a non-invasive and near-zero-cost manner.
5. Deploy, evaluate, and demonstrate the enterprise plug-n-play diagnostics and optimization solution in a minimum of 252 supermarket stores in California.

Fault detection and diagnostic algorithms can only be applied if data are available. Thus, the first step in creating a scalable, low-cost solution was creating a scalable, low-cost data collection system. It was found that the best solution is to use a distributed data storage network via cloud computing. Amazon Cloud Service was selected as the infrastructure service provider. This cloud solution enables rapid scaling for quick onboarding, numerous parallel data collection strings, and low-cost data storage, which all results in Ezenics being able to store all of the data a building can provide, for an unlimited amount of time, at a low-cost to the client. Currently the data exchange carrier is storing 555,200 data points every minute for the 252 commercial retail locations throughout California.

Rooftop units are made to be cost effective and, as a result, they are often missing sensors that provide key information. One example of this situation is a mixed air temperature sensor. A mixed air temperature sensor measures the air temperature before the cooling and heating coils. A supply air temperature sensor measures the air temperature after the cooling and heating coils and is typically available on a rooftop unit. If the mixed air temperature and the supply air temperature are known, the efficiency and operation of the heating and cooling coils can be continuously checked through the use of a fault detection algorithm.

If a physical sensor is not available, a measurement can be calculated via a virtual sensor. For example, pressure sensors are very important for fault detection in a vapor compression cycle. However, they are expensive and, as a result, pressure sensors are seldom installed in small applications such as a packaged rooftop unit. One solution is to create a virtual pressure sensor, which can calculate pressure values by utilizing the readings from a low-cost, common temperature sensor.

Through lab research and field experience it was found that five key sensor outputs could be calculated if certain criteria were met. The five virtual sensors that were created are: mixed air temperature, cooling capacity, supply air flow, refrigerant charge, and energy efficiency ratio. The virtual sensors enable remote sensor calibration and expand the list of fault detection and diagnostic algorithms that can be applied to equipment.

While studying the indoor environment, it was found that zone humidity is a point of interaction between the heating, ventilation, air conditioning and refrigeration systems. By lowering the humidity via the heating, ventilation, and air conditioning system, a net energy savings can be achieved due to the reduced energy consumption of the refrigeration system. The humidity should be lowered to a point where it takes more heating, ventilation, and air conditioning energy to lower the humidity than is saved by the refrigeration system. Additionally, by using sensor data from nearby weather stations, it was possible to check the outdoor air temperature sensors used by the rooftop units. Frequently the outdoor air temperature sensor used by the rooftop units was located in a position such that it was heavily influenced by direct sunlight. As a result, economizing operation of the rooftop units was heavily under-utilized, which means excess energy is being consumed. Only an external system that is checking and comparing programmed schedules and setpoints to their intended guidelines can detect these types of issues.

Finally, the data exchange carrier, virtual sensors, and automated fault detection and diagnostic algorithms were deployed to 252 commercial retail buildings throughout California, covering over 33,000,000 square feet. The data exchange carrier is collecting 555,200 data points continuously from the 252 locations across 5,845 HVAC machines, 1,253 lighting machines, and 4,742 refrigeration machines. There are fault detection and diagnostic algorithms implemented on all of the machines and the fault detection and diagnostic algorithms have identified 27,754 issues for a total of $3,790,096 in calculated savings.

CHAPTER 1: Introduction

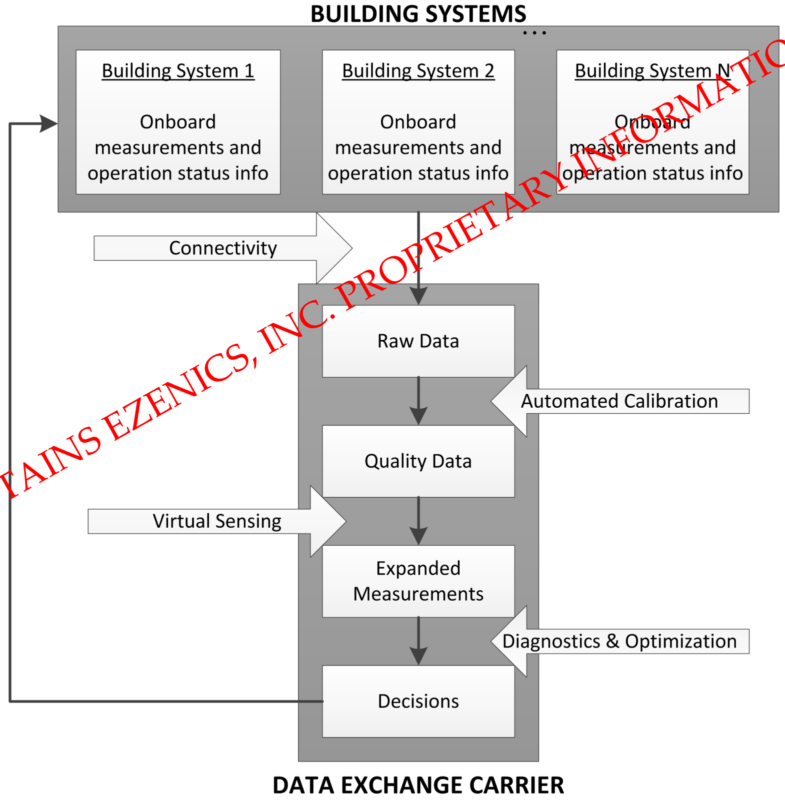
The buildings industry spends about 90 percent of its professional effort in improving the designed efficiency of equipment (Cisco, 2005) and is neglecting the operating period, where more than 75 percent of the total lifetime building cost occurs. As an example, the efficiency of new rooftop air conditioning equipment has improved substantially over the past 20 years and is now approaching practical limits that cannot be surpassed in a cost-effective manner. Unfortunately, building energy systems often do not function as well as designed due to faults introduced during installation or faults that develop during routine operation. According to the California Energy Commission (Energy Commission) (2008), the widespread lack of quality system installation and maintenance can increase actual heating, ventilation, and air conditioning (HVAC) system energy use by 20 to 30 percent, regardless of the equipment's rated efficiency. Consequently, improving the design has a very limited effect on the near-term reduction of overall energy use and peak demand in buildings. Furthermore, improving the design does not address improper installation that can result in degradated performance over the long-term operation of the equipment.

The current practice of recovering the lost energy efficiency predominately relies on retro commissioning, which is costly, time-consuming, and typically only done periodically. In response to the market demands, research on automated diagnostics and optimization for heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems has been performed over the past two decades (Dexter and Pakanen, 2001; Li and Braun, 2007). However, most of the research solutions face enormous resistance to market penetration because they cannot be implemented in a simple, low-cost manner.

As illustrated in Figure 1, the goal of this project is to develop, integrate, deploy, demonstrate, and evaluate enterprise, near-zero-cost, non-invasive, and plug-n-play Smart Buildings Diagnostics and Optimization technologies which can be immediately adopted by both new and existing buildings. In this context, the objective of "non-invasive" and "plug-n-play" means:

- The technologies are only based on existing onboard sensors without the addition of any extra, physical sensors.
- The technologies use existing information technology (IT) infrastructure for connectivity and data processing without the addition of any extra local computation capacity.
- The technologies can be remotely implemented without causing system stoppage and can be self-configured without any local initial commissioning. The objective of 'near-zero-cost' means that the cost for implementation is less than 1 percent of the annual energy expenditure of the buildings.

Figure 1: Enterprise Plug-n-Play Diagnostics and Optimzation for Smart Buildings



Source: Ezenics

To achieve these objectives, it was proposed to develop a data exchange carrier that can establish connectivity with building automation systems and equipment controls to obtain, store, and process unlimited data in a near-zero-cost manner. The data exchange carrier should be able to perform automated sensor calibration to ensure quality data. Second, it was proposed to develop low-cost virtual sensors that can expand the onboard measurements and can be used for diagnostics and optimization. With the expanded measurements from virtual sensors, these HVAC&R equipment or system-level diagnostic technologies can be increased. Third, it was proposed to develop multiple-system diagnostics and optimization technologies that address the interactions among different systems of the same type and the interactions among different types of systems in a building; having data from multiple sources in a single platform enables this flexibility. Ezenics deployed the three integrated technologies across 252 retail locations that include HVAC, refrigeration, and lighting equipment to demonstrate the field performance of the Ezenics automated fault detection, diagnostics, and impact platform (AFDDI).

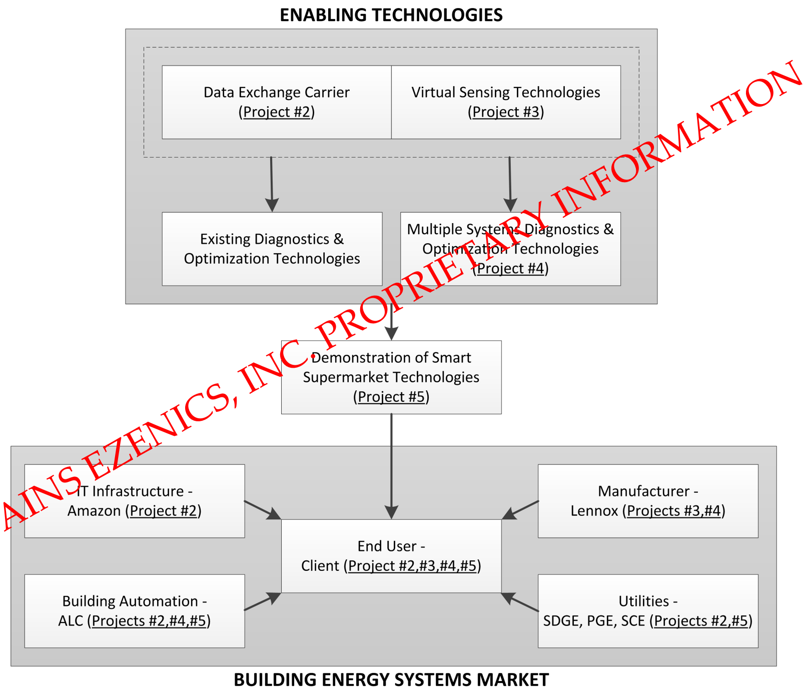
The major goal of this program is to move automated diagnostics and optimization technologies into the market through developing and enabling near-zero-cost, non-invasive, and plug-n-play technologies that demonstrate proven benefits in a scalable manner. To accomplish this, the program consists of five projects:

- Project #1 - Administration. This section is specified by the Energy Commission as a default project.
- Project #2 - Data Exchange Carrier
- Project #3 - Virtual Sensing Technologies
- Project #4 - Multi-System Diagnostics and Optimization
- Project #5 - Smart Supermarket

As indicated by the arrow lines in Figure 2, there is a hierarchy that flows from the enabling technologies to the building energy systems market. The existing diagnostics and optimization technologies and the new technologies developed in Project #4 are enabled by the data exchange carrier and virtual sensing technologies developed in Projects #2 and #3, respectively. Next, Project #5 is enabled by the existing diagnostics and optimization technologies and the new technologies developed in Project #4. Finally, Project #5 connects the whole program to the building energy system market directly.

In addition, representatives of the major players in the building energy system market have been included as industry partners. As an IT infrastructure provider, Amazon participated in Project #2 to provide IT infrastructure-related support. As a building automation system provider, Automated Logic Corporation (ALC) contributed to Projects #2, #4, and #5. One major commercial HVAC equipment manufacturer, Lennox International, provided technical support for both Projects #3 and #4. The three major utility companies in California (CA), San Diego Gas and Electric (SDGE), Pacific Gas and Electric (PGE), and Southern California Edison (SCE), provided technical support, cost share, and technology evaluation. The companies strove to include the smart supermarket technologies in marketing campaigns and aided the consumer by offering rebates and incentives to spur adoption. Academia was involved via multiple PhD researchers and experienced professors in the field from the University of Nebraska utilizing Ezenic’s state of the art, large, dual climatic chamber fault detection and diagnostics (FDD) laboratory. Finally, Target who is one of the biggest end users of the Ezenics FDD platform in California, provided demonstration sites, technical support, and significant cost share.

Figure 2: Program Connections to the Market and the Industry Partners



Source: Ezenics

The building industry has been and is reliant upon direct measurements from physical sensors to obtain the measurements of HVAC&R equipment. However, installing additional physical sensors can be expensive, problematic, impractical, or even impossible. Consequently, most of the monitoring, control, diagnostics, and optimization technologies developed in university research laboratories cannot be adopted directly in a plug-n-play manner. In 2007 Li and Braun (2007) proposed some virtual sensors for vapor compression cycle equipment for use in their decoupling-based fault detection and diagnosis methods in order to reduce implementation costs. The virtual sensors use low-cost temperature sensors together with manufacturers' rating data to derive measurements which otherwise could be expensive, problematic, impractical, or impossible to obtain directly. However, these virtual sensors were originally developed for the decoupling-based rooftop unit (RTU) FDD, since temperature sensors are relatively inexpensive and can be added as needed. Consequently, these virtual sensors typically require refrigerant side temperature measurements, which are not standard on-board sensors for existing RTUs, so these virtual sensors are not ready for the market. The market requires non-invasive, plug-n-play technologies, and the addition of sensors, even low-cost temperature sensors, should be avoided. On the other hand, the performance of some virtual sensors does require improvement. In this program, virtual sensing methods to indirectly obtain measurements where they are deemed feasible and necessary were proposed. These virtual sensors included:

- Virtual refrigerant charge sensor for vapor compression equipment with long refrigerant lines, accumulators, or receivers.
- Virtual mixed air temperature sensor for packaged rooftop air conditioners.

- Virtual supply air flow rate sensor for packaged rooftop air conditioners.
- Virtual cooling capacity sensor for packaged rooftop air conditioners.
- Virtual energy efficiency ratio (EER) sensor for packaged rooftop air conditioners.

With the growing realization of the benefits provided by automated diagnostics and optimization, individuals have performed research on the topic for HVAC&R systems over the past two decades (Dexter and Pakanen, 2001; Li and Braun, 2007). The Energy Commission has sponsored several projects on this topic as well. However, most of the research solutions face enormous resistance to market penetration because in general, the building industry is so inertial that it typically takes several decades to completely replace old technologies with new ones. The primary barriers that stand between existing research results and commercialization are the lack of cost-effectiveness, concerns for interference with normal operation, and lack of proven field performance.

The first two barriers are interrelated with each other. The more interference, the more costs are involved. The major reason for cost-ineffectiveness and interference with normal operation is that most new technologies require the client to install additional sensors on the equipment. Their discoveries are that onboard measurements are limited and can be unreliable, and adding more sensors can remedy this issue. For example, for light commercial RTUs with economizers, only the zone air temperature, outside air temperature, outside air relative humidity for enthalpy economizers, discharge air temperature, and return air temperature sensors are measured. Among these sensors, the return and outside air temperature sensors tend to be the most influended by various environmental factors such as:

- Direct sunlight hitting the OAT sensor
- Hot plenum air being returned to the unit
- RAT sensor being placed in the OAT air stream
- Exhaust or relief air reintrainment

The issues may result in the faulty operation of the outdoor air damper. Additionally, all sensors should be routinely calibrated because, over time, sensors can shift out of calibration or fail completely.

The addition of sensors leads to prohibitive implementation costs, due to the hardware costs and the installation costs. Hardware costs for data acquisition and processing keep decreasing, but the labor costs for the installation of physical sensors keeps increasing. The hardware costs of some simple diagnostic technologies for rooftop air conditioners have been reduced to as low as $10 to $20, but a method of communication is required and the installation costs for the communication hardware are up to $300. This cost problem is prohibitive enough to sabotage the penetration of diagnostics and optimization in to the market. Furthermore, adding hardware brings extra uncertainties to the original HVAC&R systems. First, it is human nature to be reluctant to be the first to use a new and invasive technology. Second, field investigation has demonstrated that the addition of pressure sensors to rooftop air conditioning systems is prone to cause refrigerant leaks (Li and Braun, 2006). The process of installing ad hoc sensors to existing units has not been as thoroughly tested as the process used by the manufacturer to add the stock sensors.

The third barrier of unproven field performance is partially caused by the first two barriers. Few technologies have had the opportunity to be implemented and deployed on a large scale. Thus, the technologies fail to demonstrate their field performance and proven benefits. Consequently, the key to diagnostics and optimization market penetration is to overcome the first two barriers through minimizing implementation costs, minimizing the interference and intrusion to the original systems, and demonstrating field-proven performance on a mass scale.

The proposed research and development results are:

- A data exchange carrier that can establish connectivity with building automation systems, equipment controls, utility, weather, enterprise applications, and protocol gateways to obtain, store, and process unlimited data, and can perform automated sensor calibration to ensure quality data in a near-zero-cost manner.
- Five low-cost virtual sensors that can expand the onboard measurements and can be used for enabling non-invasive plug-n-play diagnostics and optimization technologies.
- Multiple-system diagnostics and optimization technologies that address the interactions among different systems of the same type and different types of systems in buildings.
- Results from a minimum of 250 smart supermarkets where near-zero-cost, non-invasive, and plug-n-play diagnostics and optimization technologies are deployed.

CHAPTER 2:
Data Collection

The adoption of Internet connections in almost every commercial building along with the standardization of open protocol interfaces for the majority of equipment and building management systems (BMS) has opened the floodgates for building data, which, if analyzed, can bring significant energy and comfort benefits.

Data Exchange Carrier 2.1

The current Ezenics platform is a server-based centralized data exchange platform. The platform has proven to be efficient in handling millions of streaming data points a day for thousands of machines. In order to achieve a low-cost, adaptable, and scalable solution to collect and enable analysis of the data with collection and storage frequencies as fast as once per minute, the data exchange carrier was deployed in a cloud infrastructure, where technologies from the current Ezenics platform were converted to a cloud computing environment.

When Ezenics designed the data exchange carrier, the goal was to make a system capable of establishing connectivity with an unlimited number of building automation systems to obtain, calibrate, store, and process data at a near-zero-cost manner. In order to achieve this goal, a scalable database was required that included a dynamic provisioning mechanism that makes decisions on the capacity of the database and the application servers. The typical solution for this type of situation is a centralized server-based database. However, a centralized server was not a scalable solution since it could quickly become a resource bottleneck once it started to receive a large amount of data requests. Therefore, Ezenics decided to employ a distributed database instead of a centralized one. Furthermore, by utilizing cloud computing for the distributed database, the data exchange carrier can quickly and economically scale.

After comparing cloud services offered by several providers it was determined that the best solution for Ezenics was to utilize the Infrastructure as a Service (IaaS) provided by Amazon. In order to satisfy the Service Level Agreement (SLA) between Amazon Elastic Compute Cloud (Amazon EC2) and Ezenics, a dynamic provisioning mechanism was developed to continuously adjust the capacity of the database and the application servers.

By using a distributed database and cloud technology, data can be stored and collected for all types of equipment. The ideal data collection frequency interval is one minute. Data collected from a client's system are stored for as long as the client desires, which allows clients to access all previously collected information at any time back to the start of connectivity for each machine. For the 252 locations discussed in this project, each location is storing 300 kilobytes of data each hour. At that rate, 75 megabytes of data are stored each hour for all 252 locations, totaling 1.8 gigabytes per day.

As different protocols are needed they are coded and setup within the data exchange carrier. Currently the data exchange carrier can collect data from all of the protocols in Table 1.

Table 1: Data Exchange Carrier Protocols

Protocol	Notes
ADMCollector	Used to acquire electric power meter and sub-meter data in time intervals that vary from 1 to 15 minutes.
BACnetCollector (TCP)	Used to collect one minute interval BACnet data from facilities in 10 minute batches.
BACnet (Serial)	This method sends a request for specific points. It must be balanced so the client's system is not overloaded.
CSV File	Used to download a CSV file via HTTP, then it parses the file and loads the data to the database.
CX Telnet	Used to pull data from a Telnet Console via a polling strategy.
Continuum/Plexus	Data is collected via queries running on the tables in the Structured Query Language (SQL) database.
Desigo Alarms/Desigo V2	This is a direct Microsoft (MS) SQL database connection; the difference between V2 and Alarms is the table that data is being collected from.
Einstein E2	Used to pull data from Ultrasite. Ultrasite is the refrigeration interface created by Emerson/CPC. Through this interface a user can make changes to the setpoints, create graphs and view alarms. This protocol is especially important because of the dominance Emerson has in the supermarket industry.
Eval Service	Creates a direct connection with the Web Service and historical data can be retrieved through a web method.
Modbus (Serial)	The Modbus TCP protocol is used but with the addition of a Serial/Internet Protocol (IP) software that enables the collection of serial data through the internet.
ModbusCollector (TCP)	A range of data points can be requested in real time.
NISC Billing	Used to take downloaded utility bills and transfer that information into a database.
PGE Report	Used to transfer the electric power meter data that is being pulled directly from the utility PGE at 15 minute intervals into the database.
VBS	This method is usually used when the client server has connection to the internet but the inbound traffic is not allowed.
Voyant Carolinas	Data that is being pulled into the system directly from a Web Service. The Web Service is hosted through Voyant Carolinas, an Ezenics partner, who is receiving the data directly from a virtual private network (VPN) connection to the clients BMS.
Weather	This method acquires weather data from nearby, reliable, online weather station websites.

Source: Ezenics

Automated Sensor Calibration 2.2

Sensor measurements are the estimation of the magnitude of some attribute of an object, such as its pressure or temperature. Sensor measurements are especially important in an HVAC system, since both the HVAC system control and HVAC FDD rely on accurate sensor readings. In a feedback control system, the measurement of a controlled variable is the first step in the control process. Next, the controller compares the feedback measurement with the setpoint and finally sends a control signal to the actuators so the proper adjustments can be made to maintain the setpoint. The only way to understand how a system is performing is through the sensor readings. Any FDD algorithms that are applied to the system will use the same measurements. Without accurate sensors, neither HVAC control nor FDD will be successful. Many factors contribute to errors in physical sensor measurements, including: improper calibration before installation, sensor malfunctions and accuracy decaying due to working in harsh environment for an extended period of time, errors in the transmitter, the conversion of the sensor signal sent back to the transmitter or transducer, analog or digital conversion issues, and display resolution.

In some cases, physical sensors are not available due to economic or practical issues. If a physical sensor is not available, a measurement can be calculated via a virtual sensor. For example, pressure sensors are very important for fault detection in a vapor compression cycle. However, pressure sensors are expensive and, as a result, they are seldomly installed in small applications such as a packaged rooftop unit. One solution is to create a virtual pressure sensor that can calculate pressure values by utilizing the readings from a low-cost, common temperature sensor.

For both physical and virtual sensors, the only way of ensuring that the sensor reading is accurate and reliable is by regular calibration. However, traditional sensor calibration is an expensive process due to both the time and money required. It may be possible to calibrate the sensors for one RTU, but it is not realistic to take the temperature sensors out, calibrate them in a calibration bath, and reinstall them periodically for 252 locations.

These virtual sensors can also be used to compare the values against physical sensors to check their accuracy. This automated calibration is done by first creating a calibration environment, then by comparing the values calculated by the virtual sensors to the physical sensor values. One example of this calibration technique is measuring the saturation temperature and pressures of a refrigerant. It is very difficult to measure the temperature of a refrigerant because of oil buildup and because of the tight seal that must be maintained on the temperature sensor. In order to calibrate the temperature sensor, the pressure reading should be converted to a temperature and compared to the temperature sensor. As long as the temperature sensor is reading the saturation temperature, the values of the temperature sensor and the temperature converted from the pressure sensor should be the same. This situation is assuming the refrigerant type is known and there is no temperature glide. The virtual calibration environment is established by setting up proper criteria and the benchmark values are calculated using statistic and modeling methods from record data.

In summary, compared with traditional calibration, virtual calibration has the following benefits:

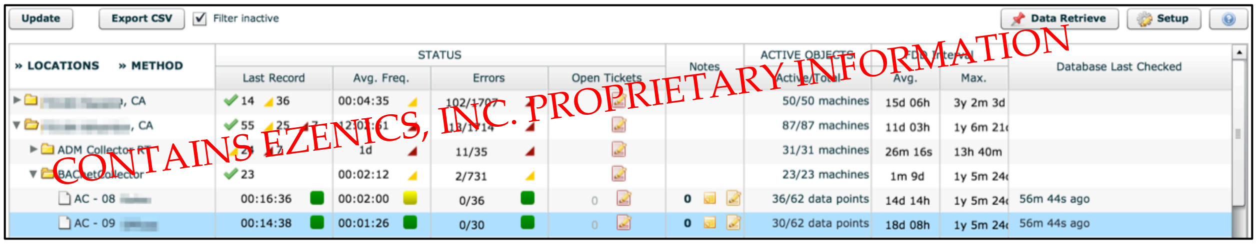
- Virtual calibration is a cost effective method. By virtually creating a calibration environment and virtually creating benchmark values, there is no need to physically set up a calibration environment and purchase additional calibrating instruments.

- Virtual calibration performed remotely, so there is no need to take the working sensor out of the system only to reinstall it after the calibration process is finished. Any potential error that may be introduced during reinstallation process is eliminated.
- Virtual calibration is a scalable calibration method. Since servers are used and not people, there is no limit on the number of sensors that can be continually self-calibrated in real-time. Furthermore, as long as the data storage is available, virtual calibration algorithms can be built into the FDD algorithm. This capability improves the robustness of a fault because it can report a sensor failure fault immediately when the fault is detected. In addition, embedding a virtual sensor algorithm within an FDD algorithm ensures that false faults are avoided due to faulty sensors. If the sensor is functioning normally, the calibration process will continue, and the calibration equation will be updated recursively using the new data. Thus, the accuracy of the FDD algorithm is improved.

Data Exchange Carrier Interface 2.3

The data exchange carrier uses a simple interface to display key information related to the location, method, and machine. By default the system will group all of the information in the following format: location, method, and machine, with location being the highest grouping as shown in Figure 3. By clicking on the locations the different methods or protocols, such as BACnet, used at that location are shown. Finally, the user can click on one of these methods and all of the equipment that uses that protocol will be displayed. If a user would like to see the method at the highest grouping level, they can drag "Method" in front of "Location" and the system will re-sort the data and update the statistics, as seen in Figure 4.

Figure 3: Data Exchange Carrier Interface - Location Grouping



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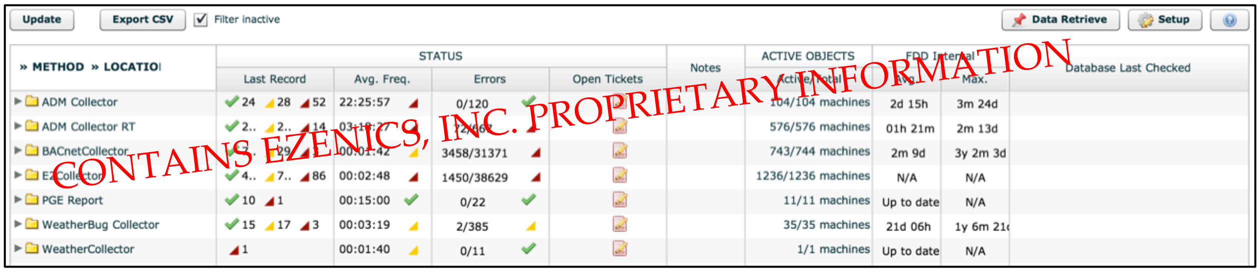
▼ [redacted], CA	✓ 55 ▲ 25 ▲ 7	12:02:51 ▲	13/1714 ▲			87/87 machines	11d 03h	1y 6m 21	
▶ ADM Collector RT	▲ 24 ▲ 17	1d ▲	11/35 ▲			31/31 machines	26m 16s	13h 40m	
▼ BACnetCollector	✓ 23	00:02:12 ▲	2/731 ▲			23/23 machines	1m 9d	1y 5m 24	
AC - 08 [redacted]	00:16:36 🟩	00:02:00 🟨	0/36 🟩	0	0	36/62 data points	14d 14h	1y 5m 24	56m 44s ago
AC - 09 [redacted]	00:14:38 🟩	00:01:26 🟩	0/30 🟩	0	0	30/62 data points	18d 08h	1y 5m 24	56m 44s ago

Source: Ezenics

Figure 4: Data Exchange Carrier Interface - Method Grouping



» METHOD » LOCATIO	STATUS				Notes	ACTIVE OBJECTS	FDD Interval		Database Last Checked
	Last Record	Avg. Freq.	Errors	Open Tickets		Active/Total	Avg.	Max.	
▶ ADM Collector	✓ 24 ▲ 28 ▲ 52	22:25:57 ▲	0/120 ✓			104/104 machines	2d 15h	3m 24d	
▶ ADM Collector RT	✓ 2.. ▲ 2.. ▲ 14	03:18:27 ▲	72/667 ▲			576/576 machines	01h 21m	2m 13d	
▶ BACnetCollector	✓ 7.. ▲ 29 ▲ 3	00:01:42 ▲	3458/31371 ▲			743/744 machines	2m 9d	3y 2m 3d	
▶ EZCollector	✓ 4.. ▲ 7.. ▲ 86	00:02:48 ▲	1450/38629 ▲			1236/1236 machines	N/A	N/A	
▶ PGE Report	✓ 10 ▲ 1	00:15:00 ✓	0/22 ✓			11/11 machines	Up to date	N/A	
▶ WeatherBug Collector	✓ 15 ▲ 17 ▲ 3	00:03:19 ▲	2/385 ▲			35/35 machines	21d 06h	1y 6m 21	
▶ WeatherCollector	▲ 1	00:01:40 ▲	0/11 ✓			1/1 machines	Up to date	N/A	

Source: Ezenics

After the user has setup their preferred grouping hierarchy, they can see the status of the different groups. Table 2 provides an explanation of the information in each column.

Table 2: Explanation of Columns in the Storage Monitor

Column Heading (Left to Right)	Explanation
Last Record	This column reports the amount of time that has passed since we recorded data from that piece of equipment, at the time the Storage Monitor info was updated. The connectivity method can influence the value displayed here, especially if data is obtained in batches.
Average Frequency (Avg. Freq.)	This column displays the average interval, in hours, minutes, and seconds, between the last 10 stored data records.
Errors	This column displays the number of storage errors that occurred out of all the total points available for that machine or location.
Notes	This feature allows notes to be written and viewed for each line item.
Active Total	This column displays the number of active machines or data points out of the total number of machines or data points, respectively.
Database Last Checked	The information in the storage monitor tool is updated for display approximately once every hour; thus the time shown in this column is when the information was last updated.

Source: Ezenics

With this simple interface users can quickly and efficiently get information on the data storage performance of their system and of the various protocols used by their facility. Once the interface was implemented, the deployment plan was created.

Field Test Plan 2.4

The following process has been developed and optimized over a series of projects to ensure accurate data storage in a scalable method. These steps will be used to complete the data storage collection for the California retail locations in this project.

1. Point retrieval from BMS.
2. Build mapping Set.
3. Utilize the Standard Label Identification and Verification Tool.
4. Setup storage for each machine.
5. Perform storage error correction.

The first step in setting up this project was to collect all of the possible data points from the client's BMS for the HVAC&R systems. There are two possible ways to get the information. The first, and easiest, is if the building owner provides Ezenics with a list of the available data points. Unfortunately, most facility owners do not have immediate access to this information. As a result, the second option is to for Ezenics to perform an investigation of the available data points. After the available data points have been gathered, they must be organized into mapping sets.

The purpose of a mapping set is three-fold:

1. To organize patterns of unique points to represent collections of machine instances in the Ezenics database.
2. To organize points to eliminate the application of conflicting standard labels.
3. To minimize duplication of work when applying standard labels.

The Mapping Set Creation Tool (MSCT) is utilized to create mapping sets and ensure data is stored in the most efficient manner for all locations. The data points are loaded into the tool and unique groups of available data points are formed based off of the machine type. The unique grouping of points are known as mapping sets and serve as an expectation of the available data points for each machine based on its type. Once the mapping sets are created, standard labels are assigned.

A standard label creates a singular definition of an incoming point that enables scalable formula implementation and delivers consistency for all users. For example, depending on the manufacturer, or the BMS vendor, the temperature measured in the supply air stream may be called supply air temperature or discharge air temperature. This inconsistency creates an issue when trying to apply formulas en masse to multiple locations and machines in a timely manner. By standardizing the name and definition of the data point, formulas can be applied quickly and easily. After the standard labels are assigned, the storage is setup for each machine.

The connectivity team then takes the Ezenics machine and mapping set information and begins data storage. As mentioned, there are many different connectivity options a client can have, so the mapping set and machine identifications are used in conjunction with the applicable method, which is already determined by the Ezenics connectivity team, to store data from the client's equipment. Once the data storage is setup, any data storage issues will be addressed. Storage errors can occur due to an offline controller, a system that is overloaded, a mapping set discrepancy, a point that is not available for the specific machine, or a path that is not correctly set.

The end result of these steps is data storage that is reliable and standardized, which is critical for automated FDD. Setting up data storage is like building the foundation of a house. Only a few people appreciate it until something goes wrong.

Field Test Results and Validation 2.5

There were three different systems that data points were extracted from. The first two were for the HVAC system and the third was for the refrigeration system. The two systems that were tried for the HVAC system were web service and BACnet. The system used for the refrigeration data retrieval was Einstein.

The web service technique entails pulling information directly from the client's BMS. The benefits to this technique are that any items displayed in the BMS can be acquired. Each item in the BMS has a path, which is used by the web service protocol to obtain data. However, there are also drawbacks associated with using a web service, which ultimately led to Ezenics pursuing a different approach.

Throughout the point list retrieval process, Ezenics communicated with the client to ensure successful data retrieval. The main drawback experienced with using a web service was the load placed upon the client's servers. The ideal point recording frequency that Ezenics uses is one minute. This frequency means that for every point that is requested, a value is recorded once every minute. The storage frequency must be balanced with the number of points being pulled, as the bandwidth required can quickly increase if the frequency and point count are not managed properly. Even though many different points are available to pull with the web service, the benefit stated above, the load placed on the client's system was too great. Since the system resources were exceeded, the issues that would have occurred would not have allowed for a continual flow of data free of interference with machine and BMS operation.

Before the web service method was stopped, Ezenics experimented with changing the variables involved. If the storage frequency is reduced in order to compensate for the higher population of points, then Ezenics analytics are impacted. Many mechanical operations, such as compressor activation and deactivation, can change in short time spans. If the storage frequency is reduced from once every minute to once every fifteen minutes, then the data resolution is too poor to accurately diagnose issues with the equipment. Therefore, the number of data points was reduced. Reducing the data points can also impact analytics, because if the necessary information is not provided then no issues can be detected. As a result, points were only removed if they were not necessary, leaving an optimized points list. However, issues with exceeding client resources were still experienced, as well as storage errors experienced because of the bottlenecked process. Consequently, a secondary method was undertaken.

Ezenics developed a tool that acquires data from points on the client's machines that are BACnet mapped. The tool can auto discover these data points, and then allow for Ezenics to pull data from each of them. While not all of the data points in the client's BMS are BACnet, the majority of the critical points are, which allow for Ezenics analytics to perform as designed. Additionally, the load on the client resources is reduced when using a BACnet connection, which allowed Ezenics to achieve the optimal data frequency of one minute. With the method in place to pull machine data and enable points list retrieval, the mapping set creation process can begin.

The refrigeration data was collected through the CPC Einstein 2 (E2) unit. The E2 units are produced by Emerson and allow for the control and provide a BMS interface for the refrigeration system. Each location utilizes several E2 controllers. This distributed load allows for data collection in two to three minute intervals. Data could be collected at a faster rate, but some of the E2 units have limited processing resources. The data are collected through the data exchange carrier. Beyond just retrieving the data points, the same communication method that is used to read the data points could be used to write a value to the BMS if a user wished to have this ability and if the BMS integrator allowed it.

After the data points were extracted, mapping sets were created. For the HVAC equipment there were a total of 23 mapping sets made and for the refrigeration equipment there were a total of 5 mapping sets made. There were fewer mapping sets required for the refrigeration equipment because they were more standardized, and there are more combinations of RTUs, such as constant volume and variable volume fans. The complete list of mapping sets that were created can be found in chapter 5. Once the mapping sets were created, they go through a verification process. This process ensures the data points are storing correctly and accurately. Occasionally certain conversions are needed to get the stored data to match the standard setup for Ezenics algorithms; any necessary conversions are applied in this step. After this process is complete for each mapping set, the standard labels were applied.

The final step in setting up the data storage for the machines was to send the needed storage setup information to the support team. The support team used the information provided to setup the machines on the Ezenics system and enabled the storage for the machines. After the storage was started, the storage errors were examined and corrected. A data storage error percentage of less than 5 percent is maintained at all times for all clients. There is typically a small percentage of data storage errors due to frequent changes in the client’s BMS and other anomalies.

CHAPTER 3: Virtual Sensors

Necessity 3.1

Embedded intelligence is a key to improving the performance of systems in terms of functionality, safety, energy efficiency, environmental impacts, and costs. Consider the progress that has been achieved with automobiles within the last two decades. Modern automobiles incorporate many intelligent features, including anti-lock brakes, electronic stability control, tire pressure monitoring, feedback on fuel efficiency, and the need for service. If a car is in need of service, then a technician has access to onboard diagnostic information. In many cases, these advanced features have been enabled through the development of virtual sensors. A virtual sensor estimates a difficult to measure or expensive quantity using one or more mathematical models along with lower cost physical sensors. Fifty years ago, most automobiles provided fuel level and some warning lights using four physical sensors, on average. Today, about 40 relatively low-cost embedded physical sensors are employed along with virtual sensors to optimize the driving performance, safety, functionality, and reliability of vehicles (Healy, 2010).

In contrast, building systems rarely provide feedback on energy efficiency or the need for service and generally do not provide optimized controls. In fact, typical information provided to a building owner and occupants, even with a direct digital control (DDC) BMS, is not significantly better than what was provided 50 years ago. Although the energy efficiency of individual building components has improved significantly, the operating efficiency is typically degraded by 20 to 30 percent due to improper installation and commissioning, and inadequate maintenance or repair (CEC, 2008).

One of the reasons that building applications are slower to adopt more automated and intelligent features than automobiles may be that they are not mass-produced in factories. For automobiles, automated features are part of an integrated design and their development costs can be spread out over millions of vehicles. For buildings, the cost threshold for advanced features is much higher because buildings tend to be individually engineered. Also, building systems can be very large and complex, serving hundreds of zones with individual controllers and often requiring thousands of sensors to adequately characterize and monitor performance. Therefore, a key to realizing more intelligent features in buildings is to reduce the cost threshold. Lowering the cost of sensing through the availability of virtual sensors helps in alleviating this problem with the potential for providing high-level performance monitoring information at lower cost. It would also make sense if advanced features were embedded within individual manufactured devices, such as air handling units or compressors, rather than being engineered within the control system during the building design phase. In order to realize widespread application, advanced features should be commodities rather than individual engineering projects.

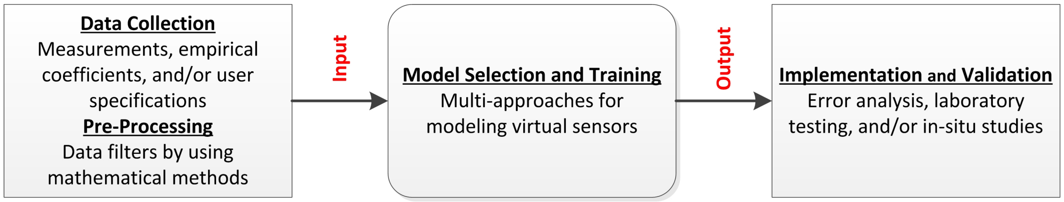
Most of the approaches that have been developed for automated diagnostics require a number of measurements that are not accurate or typically available within existing monitoring systems.

The deployment of automated diagnostics has been limited due to the lack of information caused by missing sensors that were removed because of cost avoidance. Virtual sensing techniques could facilitate the development of more cost-effective and robust diagnostic systems that can lead to improved control.

Development 3.2

In general, the process of developing virtual sensors can be defined in three steps as illustrated in Figure 5 and described in the following paragraphs:

Figure 5: General Steps in Developing Virtual Sensors



Source: Ezenics

Proper data collection and pre-processing is fundamental in the development of accurate and reliable virtual sensor models. The type and range of test data required for a valid virtual sensing model depends on the modeling approach. Transient sensors require transient test data, and transient data should be filtered for steady-state modeling approaches. A "steady-state detector" may be used as a pre-processor (Li and Braun, 2003; Wichman and Braun, 2009) to eliminate transient data. For black-box models, Principle Component Analysis (PCA) is a popular approach for pre-processing data in order to aid in the model selection.

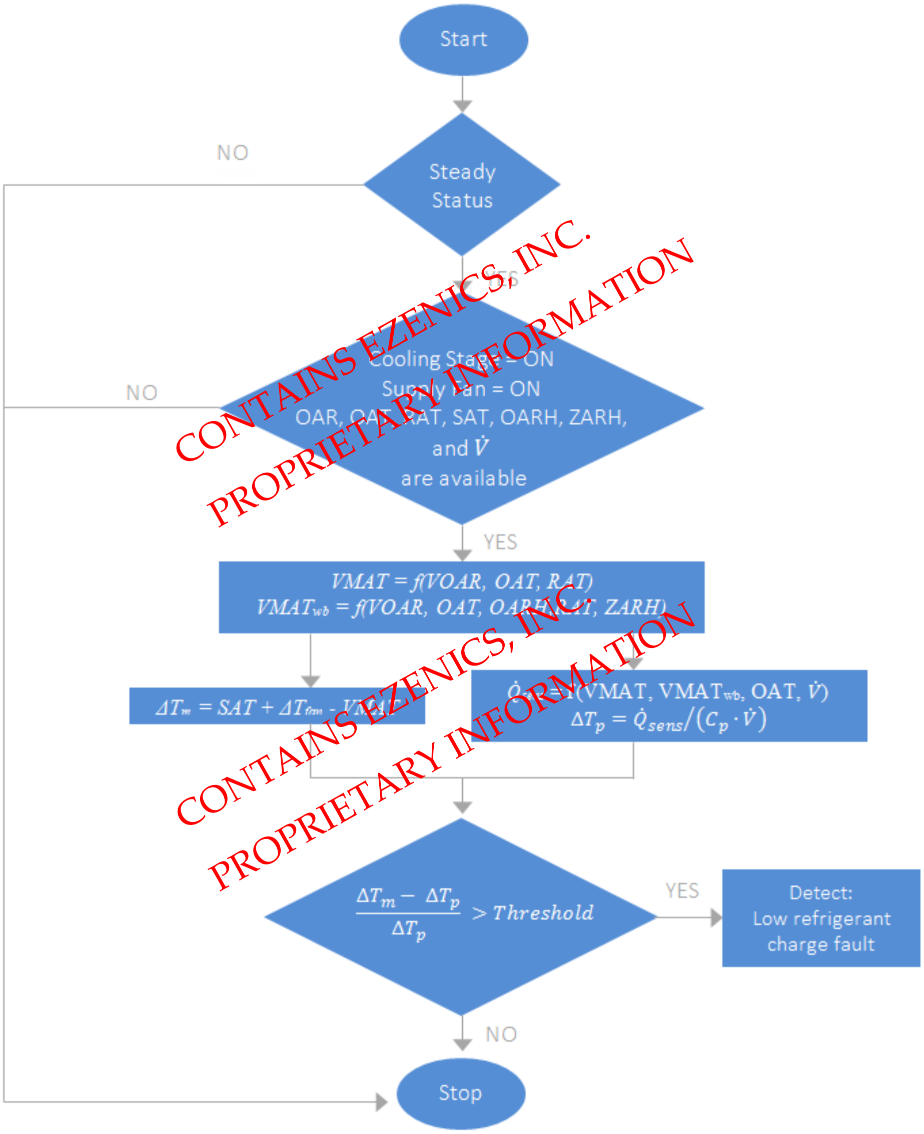
Model selection and training are the most difficult and critical steps in the process of developing a virtual sensor. There are many model types to choose from and each requires following the process of determining the proper model order, estimating parameters, and redefining the model order. There are several possible modeling approaches, and there is an art involved in identifying an appropriate model.

A virtual sensor could be implemented as part of a control or monitoring system or as a standalone sensor with its own hardware, embedded software, and input/output channels. In either case, the virtual sensor implementation needs to be tested in both laboratory and in-situ studies to validate performance and evaluate robustness, such as with an error analysis. Statistical approaches can be used to validate accuracy, such as the student's t-test (Gosset, 1908). A t-test is used to compare two sets of data and determine if they are significantly different from one another. It is important to assess the performance using independent data (Hastie et al., 2001; Weiss and Kulikowski, 1991). The virtual sensors in this project are discussed in the following sections.

Virtual Refrigerant Charge 3.2.1

The virtual refrigerant charge sensor operates as shown in Figure 6 below. The virtual sensor works by comparing the measured temperature drop to the predicted temperature drop across the cooling coil. The predicted temperature drop is calculated using a model that outputs values to calculate the sensible cooling capacity, which is then used to calculate the temperature drop. If the difference between predicted and measured temperature drop is significant enough, the low refrigerant charge issue is diagnosed.

Figure 6: Virtual Refrigerant Charge Calculation Steps



CONTAINS EZENICS, INC. PROPRIETARY INFORMATION

Source: Ezenics

The virtual low refrigerant charge sensor was validated using experiment data on a 7.5 ton test RTU in the laboratory. The refrigerant charge level was adjusted from a full charge to 40 percent of the full charge under a wide range of driving conditions. The normalized virtual refrigerant charge sensor, $RE_{\Delta T}$, was calculated as a difference from the measured temperature drop for three severity levels: normal, moderate, and severe. The definitions of the severity levels are in Table 3, as well as the different test conditions. From the results for each test condition, shown in Table 4, it can be seen that this method can successfully detect a low refrigerant charge fault before 8 percent of the sensible cooling capacity is lost.

Table 3: Testing Conditions for Virtual Refrigerant Charge

OAT Test Conditions (°F)	Cooling Stage 1 (% Full)	Cooling Stage 2 (% Full)	Severity Level
100/90/80/75	50	50	Severe
	50	70	Moderate
	50	90	Moderate
	50	100	Moderate
	60	100	Normal
	70	100	Normal
	80	40	Severe
	80	60	Moderate
	80	90	Normal
	80	100	Normal
	100	40	Severe
	100	60	Moderate
	100	80	Normal
	100	100	Normal

Source: Ezenics

Table 4: Normalized Virtual Refrigerant Charge at Severity Levels

Severity Level	$RE_{\Delta T}$
Normal	-8% ~ 0
Moderate	-25% ~ -8%
Severe	-40% ~ -25%

Source: Ezenics

Virtual Mixed Air Temperature 3.2.2

In this study, a virtual mixed air temperature (VMAT) sensor was constructed to estimate the mixed air temperature using the outside air temperature (OAT), return air temperature (RAT), and a correlated virtual outdoor air ratio sensor (VOAR). The virtual mixed air wet bulb temperature (VMATwb) sensor was constructed in a similar manner, with the addition of determining the latent component at the outside air and return air conditions.

Supply Air Flow Fate 3.2.3

In the developmental stages of the virtual supply air flow rate sensor, a cooling-based approach and a heating-based approach were studied. The heating-based approach proved more successful, with a lower overall deviation from the results.

Even though the cooling-based approach was less successful, it was still developed and tested. The primary calculation of the supply air flow rate during heating is based upon the capacity of the heating device. With different manufacturers there are varying amounts of information available about the mechanical equipment. The more detailed the capacity information that is known for an RTU, the more accurate the virtual supply air flow rate calculated by the formula will be.

When an RTU is in cooling mode, the virtual supply air flow rate calculations incorporate the latent component of heat transfer. Thus, enthalpy is used in determining the cooling virtual supply air flow rate. The same manufacturer data and sensor inputs from the heating mode apply to cooling mode. The only additional work required is to determine the enthalpy at the mixed air and supply air conditions.

In order to determine the enthalpy at the mixed air condition, the virtual mixed air temperature and virtual mixed air wet bulb temperature calculations are used. Using those values, the mixed air enthalpy can be calculated based upon the psychrometric relationship of the sensor measurements. Without the aid of the virtual mixed air sensors, the mixed air enthalpy would not be possible to obtain without special sensors, which are both expensive to purchase and expensive to install.

In order to obtain the enthalpy of the supply air, a series of checks exist in the formula due to the lack of information regarding the latent component of the supply air. If no sensors are available, such as a supply air relative humidity sensor, then an assumption based upon three conditions is made about the supply air dew point temperature. From there, the supply air enthalpy is calculated and used to determine the virtual supply air flow rate.

Cooling Capacity 3.2.4

The virtual cooling capacity sensor works in conjunction with the virtual refrigerant charge sensor. The output of the virtual cooling capacity sensor is a predicted temperature drop, which is then used to output the diagnosis of the virtual refrigerant charge sensor.

During the initial lab testing of the virtual cooling capacity sensor, the performance was evaluated using a wide range of data. Overall predictions of cooling capacity were within 10 percent for both wet and dry-coil conditions.

Energy Efficiency Ratio 3.2.5

The virtual EER sensor requires the RTU to be in the full cooling mode and knowing the cooling maximum air flow or the air flow during full cooling. For this virtual sensor it is necessary to know the enthalpy values at the mixed air and supply air conditions. Therefore, the same process that was used in determining the cooling virtual supply air flow rate is followed for determining the mixed air and supply air enthalpy within the virtual EER sensor calculation.

The final component of the virtual EER sensor calculation is the total electrical input. To determine this, the measured power, in kilowatts (kW), consumed by the RTU during full cooling is needed. A sub-meter can be used to obtain the power consumption for the specific RTU; the data exchange carrier module can store this sub-meter data in addition to the other RTU data, providing centralized storage for the virtual energy efficiency sensor calculation. However, a sub-meter is often not available for a single RTU. In that case, if available, the manufacturer's data for the rated power consumption at full cooling can be used.

Validation 3.3

The virtual sensors were tested on the equipment in the breakdown shown in Table 5. In Project #3, an independent subcontractor visited selected locations to perform on-site validation of the faults detected by the Ezenics AFDDI platform and to take measurements that were then compared to sensor readings to check the calibration of the sensors. The virtual sensors were purposely deployed and tested on the equipment examined by the subcontractor as on-site measurements and information aid in validating and learning about the performance of the virtual sensors.

Table 5: Equipment Testing for Virtual Sensors

	Total RTUs[1]	Aaon RTUs	Carrier RTUs	Lennox RTUs	Other RTUs
California	4,323	1,331	1,414	1,368	210
Locations the Vendor Visited	450	61	94	118	6
Machines Virtual Sensors Tested On	86	20	21	44	1

1. Total RTUs include single zone RTUs, RTUs with dehumidification, and RTUs serving VAV boxes
Source: Ezenics

Each virtual sensor is discussed further in the following sections. The strengths and weaknesses of each are discussed to the fullest extent possible.

Virtual Refrigerant Charge 3.3.1

The virtual refrigerant charge sensor diagnosed a low refrigerant charge on 41 percent of the test equipment. This occurrence rate aligns closely with the findings of a New Buildings Institute (NBI) report that states 46 percent of RTUs have an issue with the refrigerant circuit (Cowan, 2004). Incorporating the duration of the fault improved the reliability of the results; in an RTU with low refrigerant, there will continually be issues with the cooling capacity. Understanding the physical ramifications of the issue aids in properly identifying the diagnosed fault’s severity. Additionally, the method utilized to determine a low refrigerant charge does not only indicate low refrigerant; it can also indicate dirty coils or broken fan belts. Therefore, with additional sensors or information about the equipment, the virtual sensor calculation can be more robust.

Virtual Mixed Air Temperature 3.3.2

The virtual mixed air temperature sensor is essentially an energy balance between the outside air and return air streams. The component of the energy balance that is crucial is the outside air ratio. Accurate outside air ratio calculations are achieved through ensuring a steady-state operation before calculations are made. Items checked for steady operation include rate of temperature sensor change, rate of outside air damper change, heating operation, cooling operation, and minimum difference between outside air temperature and return air temperature. Regardless if any one of the conditions fails to surpass the set tolerances, the formula can still estimate the outside air ratio by using previously recorded data such as the outside air ratio and damper position. There are also diagnostics incorporated into the virtual outside air ratio calculation; they are only generated for non-estimated outside air ratios.

In order to create a robust virtual mixed air temperature it was important to use extra caution when creating the outside air ratio algorithm. From an analytical standpoint, the energy balance approach is sound. The addition of the checks within the virtual outside air ratio calculation further enhances the reliability of the virtual mixed air temperature sensor. The virtual mixed air temperature sensor only outputs results when the virtual outside air ratio sensor outputs results, so it is considered validated for the virtual sensors that utilize the virtual mixed air temperature sensor.

Supply Air Flow Fate 3.3.3

The usability virtual supply air flow rate output range is the highest in comparison to the virtual cooling capacity and virtual EER sensors. It can output a supply air flow for any combination of cooling or heating stages that are active. This functionality is achieved by dividing the total machine capacity by the number of stages. If additional manufacturer's information is available for each compressor staging combination, then this assumption is not necessary as the specification values can be entered into the formula.

The investigation of the supply air flow rate virtual sensor leads to several conclusions and recommendations. First, the virtual sensor can be utilized to determine poor air flow performance because of the calculated output that occurs when the mixed air (MA) and supply air (SA) conditions are similar. Additionally, there is the potential to diagnose a cooling or heating issue because of the calculated outputs that occur when there is essentially no difference from the MA condition to the SA condition even though the cooling or heating stages are active. Next, the SA latent condition assumption and the assumed cooling capacity, are limitations of this virtual sensor that cannot be avoided. The required manufacturer information to eradicate the assumptions does not exist in full, even for the most detailed specifications published by manufacturers. Additionally, due to the low-cost nature of packaged RTUs, it is unlikely that an extra humidity sensor at the SA condition will be included by default. The addition of a humidity sensor in the supply air section would provide tremendous feedback on the latent component of the air.

Nevertheless, with the knowledge of the functions of an RTU and of the assumptions made by this virtual sensor, the results are still valuable in indicating the supply air flow and potentially minor issues. If left unchecked, any minor issues could worsen. A recommendation for this virtual sensor would be to incorporate the knowledge of the specific RTU the virtual sensor is deployed on and the assumptions made by the virtual sensor, so that appropriate action occurs as a result of investigating the output of the virtual supply air flow rate sensor.

Cooling Capacity 3.3.4

The virtual cooling capacity sensor operates by using coefficients derived from the manufacturer's information within a model that calculates the cooling capacity. Due to the lack of available manufacturer information, the virtual cooling capacity sensor can only operate when the first stage of cooling is active or when all of the cooling stages are active. Therefore, the range of usability is lower than the virtual supply air flow rate sensor, but higher than the virtual EER sensor. Currently, only Lennox provides enough information for the two operating states described.

An input to the virtual cooling capacity sensor is the expected air flow during cooling. If the RTU has an air flow sensor, this can be utilized in the virtual cooling capacity sensor. However, most RTUs do not have an air flow sensor, hence the value of the virtual supply air flow rate sensor. Typically, a manufacturer's rated air flow value is used for the expected air flow during cooling. An additional method, if manufacturer's information is unavailable, is to calculate an expected air flow using the tonnage of the machine. The more assumptions that are made in determining this value, the more the virtual cooling capacity sensor will deviate from the actual value. A virtual air flow that is higher than actual air flow will output a lower expected temperature drop, and a virtual air flow that is lower than actual air flow will output a higher predicted temperature drop. It is important to understand where the expected air flow during cooling is attained, as it can influence how much effort is spent on obtaining RTU information initially. Interpretation of virtual cooling capacity results can be improved with the understanding of what the expected air flow during cooling is based upon.

The influence of the OAT and damper position is significant on the virtual cooling capacity sensor. For higher OAT and ratio of incoming outside air, the predicted temperature drop can be high as there is greater potential for cooling. For a lower OAT and damper position, the air that needs cooling is already colder, meaning the potential to cool is less and the predicted temperature drop values could be smaller. By understanding the operation of the virtual cooling capacity sensor, its effectiveness as an RTU virtual sensor is improved. The calculated values output by the virtual sensor for the test equipment were near the rated temperature drops from the manufacturer data. The difficulty in judging the accuracy of the virtual sensor is when the unit is only using the first stage of cooling because there is no cooling capacity information available from the manufacturer. However, due to the success of the virtual sensor at full cooling capacity, coupled with the understanding of the potential influences on the calculated output, the sensor can provide valuable information on the RTU's cooling ability.

Energy Efficiency Ratio 3.3.5

The virtual EER sensor is the most complicated of the virtual sensors in this project. The logic of the virtual sensor is essentially a combination of the main logical pieces of the virtual supply air flow rate sensor and the virtual cooling capacity sensor. Consequently, the strengths and weaknesses of those two virtual sensors carry through to the virtual EER sensor. Additionally, the virtual energy efficiency sensor ratio requires that a unit be in its full cooling mode. As a result, the range of usability is the lowest of the virtual sensors discussed in this project.

The virtual EER sensor is affected by cooling issues that result in the difference between the MA and SA conditions to be small or even negative. The SA latent condition assumption plagues the results of this formula as well, similar to the virtual supply air flow rate sensor. Moreover, if the expected air flow during cooling is incorrect, the virtual EER is impacted. If this situation occurs, it means that using an air flow that is higher than actual results in a higher EER output and using an air flow that is lower than actual results in a lower EER output.

A further consideration in the virtual EER sensor is the power consumption that is needed to calculate the EER. In this project, it was determined that there is variance in the power readings at full cooling. Three different types of measurements were taken for the power at full cooling, and the results are shown in Table 6. The table includes manufacturer rated power, power measured on-site by Katin Engineering Consulting (KEC), and sub-meter readings. The manufacturer rated power was utilized as the most accurate.

Table 6: Power at Full Cooling - Three Different Measurement Types

Location	Machine	Mfgr. Rated Power	KEC Measured Power	% Diff (Mfgr. in Denom.)	Power Meter Data - Avg.	% Diff (Mfgr. in Denom.)
52	AC - 14 Checklanes[1]	-	-		-	-
96	AC - 12 Mini Seasonal[1]	-	-	-	-	-
96	RTUD - 16 Seasonal	22	19.7	10.50%	10.9	50.45%
103	AC - 06 Checklanes/Girls	14.3	13.43	6.10%	10.2	28.67%
103	AC - 08 Market	14.3	14.7	2.80%	5.4	62.24%
103	AC - 12 Toys	14.3	14.3	0.00%	12.4	13.29%
103	AC - 13 Fitting Room	14.3	14.1	1.40%	13.3	6.99%
103	AC - 15 Sporting Goods	14.3	14.3	0.00%	13.1	8.39%
147	AC - 16 Hshld Comm[1]	-	-	-	-	-
147	AC - 19 Stockroom[1]	-	-	-	-	-
187	AC - 12 Bodywear	21.2	27.6	30.20%	12.2	42.45%
187	AC - 14 Sporting Goods	21.2	28.7	35.40%	19.1	9.91%
204	AC - 08 Market	15.4	16	3.90%	-	-
204	AC - 09 Intimate App	22	25.1	14.10%	19.3	12.27%
204	AC - 10 Home Improv	18.3	19.7	7.70%	-	-
204	AC - 11 Home Decor	22	24.4	10.90%	-	-
204	AC - 12 Shoes	22	23.1	5.00%	17.3	21.36%
208	AC - 09 Intimate App	22	32.5	47.70%	21.8	0.91%
208	AC - 10 Home Improv	18.3	19.5	6.60%	16.6	9.29%
216	AC - 08 Market	22	25.8	17.30%	-	-
216	AC - 12 Mens	22	25.8	17.30%	22.8	3.64%
216	AC - 13 Electronics	22	27	22.70%	-	-
216	RTUD - 06 Checklanes	22	27.5	25.00%	23.1	5.00%
216	RTUD - 14 Sporting Goods	22	26	18.20%	24.2	10.00%
237	AC - 07 Marking	9.9	10.4	5.10%	12.5	26.26%
237	AC - 08 Stock	9.9	10	1.00%	11.1	12.12%

1. Unit did not have adequate manufacturer data.

Source: Ezenics

Analyzing the inputs and results of the virtual EER sensor reinforce the fact that knowledge of the virtual sensor operation is critical in judging the outputs of the sensor. As the complexity of the virtual sensor increases, the importance of having that knowledge increases. Similar to the previous virtual sensors, the virtual EER sensor can provide valuable information about an RTU's ability to cool, but can be vastly improved with further knowledge of the equipment.

Results 3.3.6

Upon detailed investigation into the five virtual sensors, the results were varied. Upon further investigation the pros and cons of each formula were revealed, and the importance of understanding how each formula works was demonstrated.

The first point to understand is that the formulas are closely related to each other. The virtual mixed air temperature is a dependency for the other four virtual sensors. Also, the virtual supply air flow rate, cooling capacity, and EER sensors all interact with each other under different unit conditions. For example, when there is a cooling failure or inefficiency, the virtual supply air flow rate sensor outputs are very high or very low, negative values. The virtual cooling capacity outputs a low delta-T value and diagnoses a fault, and the virtual EER sensor outputs a low EER. This situation also applies during heating.

Understanding that the formulas are closely related is critical when analyzing the results output by the virtual sensors. If only one of the virtual sensors is being analyzed, such as the virtual supply air flow rate sensor, the values may seem useless or incorrect. In reality, the unit could be experiencing a cooling issue, causing the virtual supply air flow rate sensor to output extremely high or low values. When the three virtual sensors are analyzed simultaneously, it is possible to find the source of what's causing the results for all three virtual sensors and make sense of what the unit is actually doing. Once the source of the issue is determined, correct action can be taken to resolve the situation. Interpreting the results of the virtual sensors properly prevents useless fixing efforts and builds confidence in the virtual sensors and the potential for virtual sensing technology.

There are potential improvements that can be made to the virtual sensors. Additional filtering to the calculated outputs could be added to better inform the user of what is actually happening to the unit. For example, incorporating an additional time component or further unit information from the manufacturer could influence the robustness of the virtual sensors. Improving upon the virtual sensor logic would be an iterative process as each change made should be analyzed to determine the change in results so that further changes can be made and analyzed. If this process was persued, the results would improve, meaning that the required amount of interpretation needed would be reduced. Thus, the user could understand what the results mean faster without needing complete knowledge of the virtual sensor. Adoption of these virtual sensors could be improved with these changes.

Further improvements could come in the form of additional information about the unit utilizing the virtual sensors. Many sources of error in the results explained above were due to expected air flows, power consumption, and lack of manufacturer information. One example is that the virtual cooling capacity is entirely limited to Lennox machines because of available manufacturer data. Even with Lennox machines, only cooling capacity for the first stage of cooling or all stages of cooling is possible to calculate. The outputs of the virtual sensors are only as good as the inputs, so there is value in obtaining appropriate and sometimes any information at all from the onset of working with the RTUs.

Overall, these virtual sensors are usable for data collection and as FDD inputs. The potential flaws of the virtual sensor calculations come from the amount of required information and how often these virtual sensors can output values. With some massaging of formula logic and information-gathering, the improvements to the virtual sensor reliability can be realized. Building owners will only benefit more in regards to the operation and maintenance of their RTUs as these virtual sensors are further improved.

CHAPTER 4:
Multiple System Diagnostics

Equipment Interaction 4.1

In order to optimize the interactions between the HVAC and refrigeration systems in a commercial retail space, it is important to understand the parameters of the interaction. There is not a direct physical linkage between the HVAC and refrigeration systems, but there has to be an interaction because the refrigeration system exists within a space that is conditioned by RTUs. Manufacturer information shows that as the ambient humidity and temperature rise, a display refrigeration case will consume more energy. However, as the temperature and humidity are decreased in a space by the HVAC system, the HVAC system will consume more energy. This situation leads to three forms of optimization:

- The HVAC system must be functioning properly, which means it is free of mechanical and operational faults.
- The refrigeration system must be functioning properly, which means it is free of mechanical and operational faults.
- If the first two conditions have been meet, the two systems can be balanced based on the energy consumption of the refrigeration system in comparison with the HVAC system to achieve the lowest possible energy consumption.

Before discussing the proper function of the HVAC and refrigeration systems, the interaction of the systems must be understood. Between the HVAC and refrigeration systems there lies an interaction in the indoor air temperature and humidity. As the indoor humidity setpoint is lowered on the HVAC equipment, the HVAC equipment will consume more energy, but the refrigeration system will consume less energy. This creates an equation that can be optimized:

↑ HVAC Energy Consumption = ↓ Humidity = ↓ Refrigeration Energy Consumption

The equation should be utilized to achieve the greatest net energy savings between the HVAC and refrigeration systems. Unfortunately, there is not a blanket solution because each location will have a different amount of HVAC and refrigeration equipment. For example, if a retail location was 200,000 square feet and had one refrigeration door that they sold ice cream goods out of, it would not be worth lowering the humidity setpoint of the entire store so the one refrigerated case could run more efficiently. The savings from the refrigerated case would not outweigh the energy spent to lower the humidity in the store. On the other hand, if a grocery store was 50,000 square feet and the floor was 70 percent covered in refrigeration cases, it might be worth running the HVAC system at 100 percent capacity to lower the humidity.

To analyze this need for optimization further, consider some starting conditions:

- Indoor dew point of ‘y’.
- Indoor dew point minus one degree ‘y-1’.
- HVAC energy consumption as a function of dew point = H(y).
- HVAC energy required to maintain the space at a dew point minus one degree = H(y-1).
- Refrigeration energy consumption as a function of dew point = R(y).
- Refrigeration energy used as a result of lowering the dew point one degree = R(y-1).

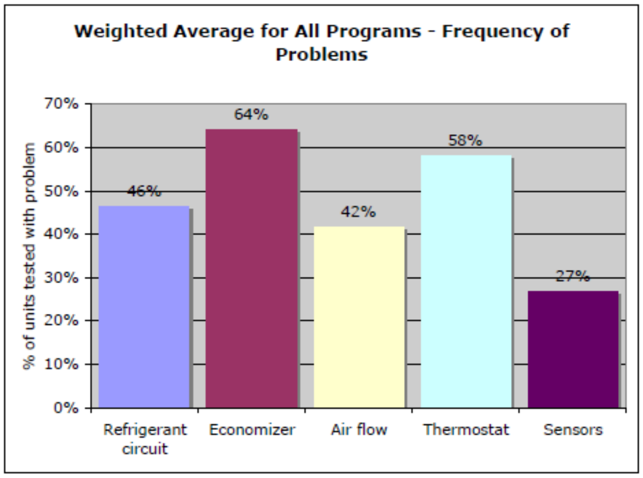
From these conditions, the following general equation can be created:

$$H(y-1) - H(y) > R(y) - R(y-1)$$

If the HVAC energy consumption used to lower the dew point one degree is less than the energy consumption saved by the refrigeration system, the dew point should be lowered. This function can be repeated until the net energy saved is at its highest. This point of maximum net energy does not necessarily occur when the increased energy consumption by the HVAC system equals the saved energy consumption by the refrigeration system.

Before optimizing the indoor humidity, both the HVAC and refrigeration systems should be free of mechanical and operational faults. Problems can occur at the mechanical level and on the control level. In an NBI report titled “Review of Recent Commercial Rooftop Unit Field Studies in the Pacific Northwest and California” (Cowan, 2004) and as Ezenics has uncovered with both HVAC and refrigeration equipment, the number of equipment issues is overwhelming. The results from the NBI report are shown in Figure 7.

Figure 7: Average Percent of Issues found in RTUs



Source: NBI Report 2004

Mechanical issues are problems with the functionality of the equipment and can cause problems in two general areas: comfort and energy. For example, if an outside damper was stuck open during the cooling season, the RTU may have to use additional energy to cool the air. If the cooling load was too high for the RTU, the zone temperature could increase, causing discomfort. The mechanical problems are not isolated to one specific component of the RTU. Issues can exist with fans, sensors, outdoor air dampers, economizers, and compressors. All of these problems contribute to increased energy consumption (kWh) and demand (kW).

In addition to the types of mechanical problems that the NBI report noted, there are also control issues related to maintaining correct or intended equipment schedules and setpoints. These control issues can go undetected using traditional FDD techniques and on-site inspection because they are not the result of equipment malfunction, they may not cause client discomfort, and, in the case of refrigeration, they may not increase the food spoilage rate.

An RTU that is cooling or heating an unoccupied space using the incorrect heating and cooling setpoints is a good example of this type of control opportunity. The equipment is working well and no occupant discomfort is observed. However, by conditioning a space with no occupants in it, energy is being wasted. Another example is a lowered cooling setpoint. A client may have operating guidelines that state the cooling setpoint is 73 degrees Fahrenheit for a given space. It is not unusual to find RTUs that are set to operate at a cooling setpoint of 71 degrees Fahrenheit. There are a number of possible reasons as to why the lower setpoint was programmed into the BMS: compensating for an adjacent zone that was failing, poor thermostat location, or diffuser position creating a complaint. Lowering the setpoint is often believed to be a fast and easy fix, but it typically hides the root cause of an issue. Furthermore, the change is often intended to be temporary, but then is forgotten and never changed back after the root cause was resolved. Similar temporary changes to equipment schedules are more common and often more costly.

Because the machine is operating as programmed, neither incorrect setpoints nor incorrect schedules are considered a fault by machine-level analytics. However, the programmed schedule or setpoint still does not match the client's operational intent. Only an external system that is checking and comparing programmed schedules and setpoints to their intended guidelines can detect these types of issues.

It is also important to make sure the sensors that are controlling the HVAC and refrigeration systems are in sync. Facilities may use one set of indoor air temperature and indoor air humidity sensors for the HVAC systems and another set for the refrigeration system, leading to differences in value. If the sensors linked to the refrigeration system are reading values too high compared to the actual, the refrigeration system will not run efficiently. The refrigeration system will be calling for a higher anti-sweat heater output when it is not necessary, which wastes energy. Furthermore, if the sensors linked to the HVAC system read values that are low compared to the actual, the system will not properly dehumidify the space. As a result, the refrigeration system will perform the dehumidification by default, which is much less efficient than if the HVAC system performed the dehumidification. Both the refrigeration and HVAC systems should be clear of operational and mechanical faults before optimization of the system interactions occurs.

Full Deployment 4.2

The first step in optimizing the interaction between the HVAC and refrigeration system is identifying the control and mechanical issues. Second, after the mechanical and control issues have been corrected, the operation between the two systems can be optimized.

The following process has been developed and optimized over a series of projects to ensure accurate selection of formulas that can be rapidly applied in a scalable manner. Once all of the data storage was setup, the following steps ensued:

- Collected machine information through a Client Questionnaire.
- Uploaded machine data into system with the Machine Parameter Tool.
- Used the Template Selection Tool to identify applicable formulas.
- Implemented and validated selected formulas.
- Tracked and resolved formula errors.

There were 252 locations that had analytics setup. The stores range in size from 80,000 to 215,000 square feet. The stores are typically made up of a general merchandise section and a grocery section. The analytics deployed are dependent on the equipment available at each location. Table 7 below summarizes the equipment information across the CA locations:

Table 7: Summary of Machine Types at 252 CA Locations

Machine Type	Count
Air Handling Unit (AHU)	20
Fan Coil Unit (FCU)	23
Single Zone Rooftop Unit (RTU)	3,818
RTU with Dehumidification (RTUD)	302
Air Terminal Unit (ATU)	1,468
Unit Heater (UH)	31
Variable Air Volume (VAV) RTU	183
Refrigeration Cases	4,046
Refrigeration Compressor(s)	298
Refrigeration Anti-sweat Heaters	143
Refrigeration Condenser(s)	255

Source: Ezenics

The specific issues inspected for both HVAC and refrigeration are as follows:

HVAC

- Outdoor air damper modulation
- Economizer enable/disable settings
- Energy recovery wheel effectiveness
- Supply fan operation
- Cooling coil heat transfer and charge
- Cooling coil valve operation
- Store humidity
- Sensor operation
- Occupied cooling setpoints
- Unoccupied cooling setpoints
- Occupied times
- Unoccupied times

Refrigeration

- Defrost cycle count
- Defrost cycle duration
- Case temperature
- Anti-sweat heaters
- Condenser pressure
- Evaporator pressure
- Sensor operation

Results 4.3

The following tables display the control and mechanical faults found at the 252 California locations after the algorithms were applied:

Table 8: Control Fault Summary - Multiple System Diagnostics

	HVAC		Refrigeration				
	Schedule	**Cooling Setpoints**	**Defrost**	**Case Temp**	**Anti-Sweat Heaters**	**Alarms**	**Pressure Setpoints**
Total Faults	3,766	2,728	1,797	706	42	1,565	134
Avg. / Location	15.06	10.91	7.19	2.82	0.17	6.26	0.54

Source: Ezenics

Table 9: Mechanical Fault Summary - Multiple System Diagnostics

	Economizer[2]	**Cooling Coil**[3]	**Humidity**[1,4]	**Sensor**[5]
Total Faults	2,002	10,884	149	2,396
Avg. / Location	8	43.5	0.5	9.5

1. A humidity fault is on a store level, not a machine level. There can only be a maximum of one humidity fault per location.
2. Economizer issues consist of: unresponsive dampers, economizer setting not followed, economizer settings not optimized.
3. Cooling coil issues consist of: cooling stage failure, cooling stage inefficiency, setpoints not met, and simultaneous heating and cooling.
4. Humidity issues consist of: high zone dew point.
5. Sensor issues consist of: stuck sensor values, sensor values too high, and sensor values too low.

Source: Ezenics

It was expected that as the number of HVAC mechanical and control issues decreased that there would be fewer refrigeration and humidity problems. With a total of 26,169 combined HVAC and refrigeration mechanical and control faults and an average of 104 faults per location, it was too difficult to discern the exact details of the relationship between the refrigeration and HVAC system. However, it was clear that there were many HVAC control and mechanical issues and there were many humidity issues. While correlation does not imply causation, HVAC issues will drive indoor humidity up and refrigeration systems will use more energy in a humid environment.

Genrally speaking, as HVAC mechanical issues are corrected, indoor humidity issues should be reduced and refrigeration energy consumption should decrease. After the issues are corrected, the owner should pursue further optimization of the systems by using the HVAC system to decrease the humidity levels to a point where the net energy difference between the HVAC and refrigeration systems produces the greatest savings.

CHAPTER 5:
Smart Supermarkets

Deployment Plan 5.1

The following process has been developed and optimized over a series of projects to ensure accurate data storage and scalable analytic implementation. Ezenics employed these steps in this project to deploy the data exchange carrier and the AFDDI modules across 252 locations.

1. Client Questionnaire - This task requires the building owner to fill out a questionnaire about general location information and the on-site equipment. The questionnaire requires that each machine be classified under its proper machine type, such as RTU, ATU, or FCU. After the machine type is established, a specific set of information is requested for each machine type. The information that is input by the client is important as it will be used in tools to help identify available formulas and for impact calculations.
2. Download Points Lists from BMS - Lists of all points for potential data storage are compiled in a points list for each machine from the BMS with original point name, original point abbreviations, object names, object type, object instance, and the point Graphical Query Language (GQL) path. The criterion is that each point is available via BACnet over IP.
3. Build Mapping Sets - Similar machine types with the same manufacturer or control program may have a similar set of available points and data types. An example would be when a building has eight Lennox RTUs. Each RTU may have a different number of cooling stages, but a generic data storage template, called a mapping set, can be made to encompass these differences for scalability purposes within the Ezenics system. The mapping sets are created to determine the total number of available points in groups of similar machines. The mapping sets are refined and uploaded to the Ezenics site in Step 5.
4. Standard Label Identification and Verification Tool - Each mapping set is plugged into the Standard Label Identification and Verification Tool. A standard label is what Ezenics has defined as the normalization of a point name for analytics. Each client may have a different naming method for the points in each machine. Standardizing the different point names into Ezenics' format is very important as the algorithms call upon data associated with each standard label name. There are three major processes within the Standard Label Identification and Verification Tool: identification, verification, and conversion. Every process must be completed for each mapping set in order to move on to the next step.
5. Mapping Set Completion - The mapping set is now uploaded to the Ezenics site. After the upload, standard labels, conversions, and circuit numbers are added to the mapping set for the corresponding points. As stated in previous steps, standard labels are used for point normalization for formulas. Conversions are used for points that need adjusted to match the Ezenics standard label definition. Circuit numbers correspond to points that

work in steps. For example, with four stages of cooling, the sequence of operation is based upon the cooling load. The sequence in which the cooling stages are engaged is taken into account in the mapping set.

6. Setup Storage for Each Machine - Storage is setup for each machine by first determining which mapping set best fits the machine type given its available points and machine type. The IP address for the location is taken from the client's BMS as well as all controller device numbers for each machine at the location. These are used to develop a configuration sequence that is used to collect data from the machine. The final step is then to assign the BACnet address corresponding to the point taken from the client's BMS system. A tool was developed using the GQL paths to automatically assign these addresses. For quality control, the essential points needed for analytics are checked to ensure the correct BACnet addresses have been assigned.
7. Storage Error Correction and Storage Validation - Storage errors can occur for a variety of reasons and must be corrected so values can be pulled from the controller. To help in this correction process, error messages are output from the Ezenics Storage Monitor to help the user determine what steps are necessary for error correction. Additionally, the data points on each machine are validated to ensure that we are storing what we expect. This process is essential because if storage is not validated, the analytics applied in future steps will generate incorrect results.
8. Machine Parameter Tool - Machine parameters are the characteristics of the machine used in determining the monetary impact of a fault occurring on said machine. The purpose of the machine parameter tool is to quickly and accurately produce and implement machine parameters so that impact can be immediately viewable as initial faults are produced. Once the proper inputs are placed into the tool, the tool is run to complete all calculations so that the necessary machine parameters can be uploaded into Ezenics' system.
9. Formula Analytic Identification - The purpose of the Template Selection Tool is to quickly, accurately, and consistently identify formulas implementable to client equipment. The tool uses the list of data points from each mapping set and its corresponding standard labels to identify which formulas to apply. It also identifies standard formula/template combinations that have a high percentage of matching points, which may be able to be manually configured into implementable non-standard templates. Lastly, it has the ability to document implementation errors, track the verification of formulas, and provide summary statistics.
10. Formula Analytic Implementation - Formulas are implemented with the Diagnostics Settings Tool. This tool is built within the Ezenics system and is used to implement formula templates, both standard and non-standard. Standard templates are built into the system for quick implementation once they are identified by the template selection tool. Non-standard templates can also be developed from standard templates when certain points are unavailable but alternate points are available. An example of a situation requiring a non-standard template would be when a standard template

typically uses a cooling stage command but can be adjusted to use the cooling stage status when the command point is unavailable.

11. Formula Analytic Validation - The Template Selection Tool is also used for formula analytic validation to give both a high level and detailed level insight to the progress of formula implementations. It can track the progress of implementations on a given mapping set for both automatically discovered formula/template combinations and user identified formula/template combinations.

The results from these steps are covered in the following sections. Discussion of on-site validation procedures is also included. The final section discusses the results of the AFDDI module across the 252 locations.

Connectivity Results 5.2

Mapping Sets 5.2.1

As a result of setting up the 252 locations, many different mapping sets were created. Table 10 displays all of the mapping sets for each equipment type with a total count of mapping sets at the bottom of the table. The weather equipment type represents the professionally maintained weather stations that Ezenics uses with its analytics.

Table 10: Mapping Set Summary by Equipment Type

HVAC	Refrigeration	Lighting	Power Meter	Weather
Demand Response	Anti-Sweat Heaters	Lighting Exterior	Power Meter - BACnet	Weather
ERV (Energy Recovery Ventilator)	Cases/Circuits	Lighting Interior	Power Meter - General	-
FCU	Condensers	-	Power Meter - RTU	-
Global	Global Data	-	Power Meter - Store	-
RTU 1 with Dehumidification: Constant Volume	Suction (Compressors)	-	Power Meter - Utility	-
RTU 1: Constant Volume	-	-	-	-
RTU 2 with Dehumidification: Constant Volume	-	-	-	-
RTU 2: Constant Volume	-	-	-	-
RTU 2: Variable Volume	-	-	-	-
RTU 3 with Dehumidification: Constant Volume	-	-	-	-
RTU 3 with Dehumidification: Variable Volume	-	-	-	-
RTU 3: Constant Volume	-	-	-	-
RTU 4 Dual Path	-	-	-	-
RTU 4 Single Path: Constant Volume	-	-	-	-
RTU 4 Single Path: Variable Volume	-	-	-	-
RTU 5: Constant Volume	-	-	-	-
UH	-	-	-	-
VAV Bypass	-	-	-	-
VAV Multizone	-	-	-	-
VAV RTU: Bypass RTU	-	-	-	-
VAV RTU: Bypass VAV	-	-	-	-
VAV RTU: Single Zone	-	-	-	-
VAV Singlezone	-	-	-	-
Total: 23	Total: 5	Total: 2	Total: 5	Total: 1

Source: Ezenics

Machine Parameters 5.2.2

A machine parameter is a field of information created for each machine that gets setup in the Ezenics platform. Machines often have multiple machine parameters in order to contain the crucial nameplate information. Machine parameters are static values, such as tonnage, as opposed to dynamically changing values, such as the zone temperature. Different types of equipment require different machine parameters as machine operation varies. Even within a category of equipment, such as HVAC, different machine parameters are required as a packaged RTU without dehumidification capability operates differently than an RTU with dehumidification capability.

For HVAC and lighting equipment, the following table displays the typically used machine parameters. As mentioned, not all machine parameters in the table will apply to each piece of HVAC and lighting equipment.

Table 11: Typical Machine Parameters: HVAC and Lighting

Machine Parameter Name	Machine Parameter Abbreviation	Units
Purchased Chilled Water Cost	CHW_Cost	$/Ton
Cooling Capacity	CLG_Capacity	Ton
Cooling Efficiency Type	CLG_Efficiency_Type	NA
Average Cooling Air flow	CLG_FLWavj	CFM
Cooling Lockout Outside Air Temperature	CLG_Lockout_OAT	deg F
Cooling Source	CLG_Source	NA
Cooling Stages	CLG_Stages	NA
Cooling Efficiency	CLGeff	kW/ton
Coefficient of Performance	COP	NA
Economizer Temperature Disable Setpoint	ECONda_Espt	Btu/lb
Economizer Temperature Enable Setpoint	ECONda_Tspt	deg F
Economizer Enthalpy Disable Setpoint	ECONen_Tspt	deg F
Free Cooling Temperature Setpoint	FCspt	deg F
Heating Capacity	HTG_Capacity	Btu/h
Average Heating Air flow	HTG_FLWavj	CFM
Heating Lockout Outside Air Temperature	HTG_Lockout_OAT	deg F
Heating Source	HTG_Source	NA
Heating Stages	HTG_Stages	NA
Heating Efficiency	HTGeff	%
Electricity Cost	kWH_Cost	$/kWh
Model Number RTU	Model_Number_RTU	NA
Minimum Outside Air Ratio	OA_Ratio_Designmin	decimal
Minimum Outside Air Damper Setpoint	OAD_MINspt	%
Purchased Steam Cost	STEAM_Cost	$/1000lbs
Gas Cost	THERM_Cost	$/Therm

Source: Ezenics

The specific machine information to create the machine parameters in the table above are gathered from clients through a client questionnaire as well as the client's BMS, if necessary. In Table 12 below, the machine parameters listed are calculated by Ezenics based upon the location characteristics.

Table 12: Calculated Machine Parameters: HVAC and Lighting

Machine Parameter Name	Machine Parameter Abbreviation	Units
Cooling Yearly Hours	CLG_HRS_YR	Hr
Cooling Average Outside Air Temperature	CLG_OATavg	deg F
Heating Yearly Hours	HTG_HRS_YR	Hr
Heating Average Outside Air Temperature	HTG_OATavg	deg F
Specific Volume	Specific_Volume	ft^3/lb

Source: Ezenics

Power meters and refrigeration equipment do not have as many machine parameters as the HVAC and lighting machines typically do. This difference in machine parameter count is due to the operation of these machines. Table 13 displays the power meter machine parameters and Table 14 displays the refrigeration machine parameter.

Table 13: Typical Machine Parameters: Power Meters

Machine Parameter Name	Machine Parameter Abbreviation	Units
Machine Prefix	MachinePrefix	NA
Power Meter Scope	PowerMeterScope	True/False

Source: Ezenics

Table 14: Typical Machine Parameters: Refrigeration

Machine Parameter Name	Machine Parameter Abbreviation	Units
Machine Prefix	MachinePrefix	NA

Source: Ezenics

Machine parameters are crucial for understanding machine operation. Quantifying the magnitude of a fault to a client relies upon machine parameter information. In addition, algorithms are improved with machine parameter information as their availability and accuracy increases.

On-Site Formula Validation 5.3

In an effort to test and fine-tune accuracies of the technologies prior to implementation on the entire California portfolio, 24 locations were chosen for on-site validation of the FDD fault results. Bob Katin of KEC performed on-site sensor, fault, and no fault validations for various machines.

Sensors 5.3.1

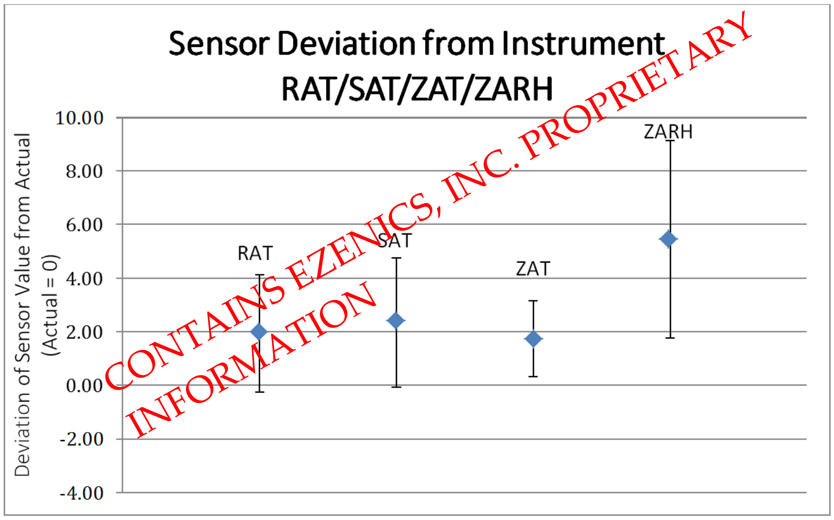
For the sensor comparison measurements, a FLUKE 975 Air Meter Test Tool and a Fluke 561 IR Themometer were used to take the baseline temperatures. Indoor sensor results for RAT, supply air temperature (SAT), zone air temperature (ZAT), and zone air relative humidity (ZARH) revealed that the sensor deviation from the instrument measurement is relatively small when observing the average deviation of the sensor value from the measured value. The results shown in Table 15 and Figure 8 also show that significant deviations from the actual values do exist even though the average value of similar sensor types may lie close to the actual value. For example, out of 61 RAT sensor readings taken, the average deviation from the actual measured value was 1.93 degrees Fahrenheit and the standard deviation from this average was ±2.19 degrees Fahrenheit. The average value of 1.93 degrees Fahrenheit is excellent in terms of portraying the reliability of the sensors, but a standard deviation value of ±2.19 degrees Fahrenheit shows that the sensor values composing that average varied significantly.

Table 15: Indoor Sensor Validation Results

	RAT	SAT	ZAT	ZARH
N	61	147	141	47
Average	1.93	2.34	1.74	5.45
Median	1.10	1.60	1.30	4.50
Min	0.00	0.00	0.00	0.30
Max	10.40	11.10	7.10	16.40
Std. Dev	2.19	2.41	1.41	3.68

Source: Ezenics

Figure 8: Sensor Deviation from Actual - Indoor Sensors



Source: Ezenics

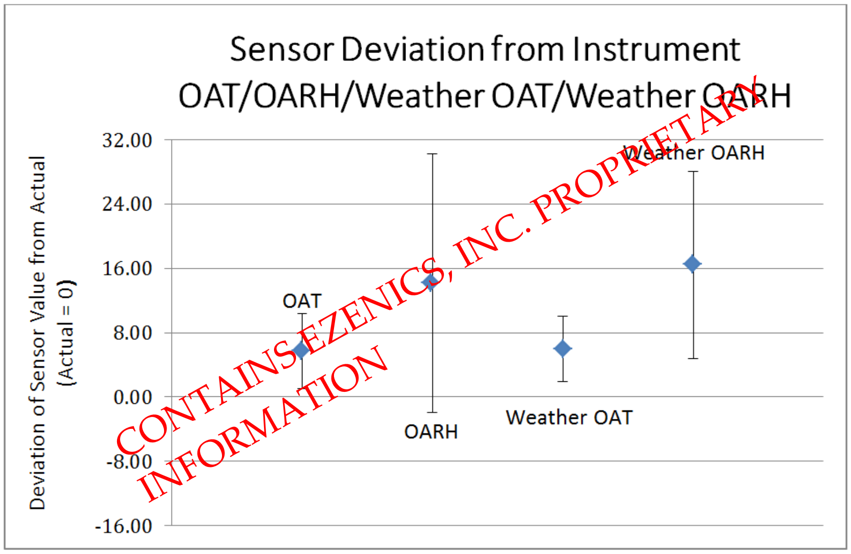
Two sets of OAT and outside air relative humidity (OARH) sensors were compared to the instrument sensor reading: the client's Global machine which broadcasts to the other machines at the location and Ezenics' weather station data. When possible, the instrument sensor readings were taken multiple times at each location, throughout different times of the day. As a result, there were approximately 60 sets of data to compare with the Global machine and Ezenics' weather machine. The results can be seen in Table 16 and Figure 9.

Table 16: Outdoor Sensor Validation Results

	Global Machine		Weather Station	
	OAT	OARH	OAT	OARH
N	61	60	61	57
Average	5.68	14.19	6.00	16.41
Median	4.25	6.15	5.10	13.80
Min	0.10	0.30	0.20	0.40
Max	18.90	72.90	17.40	45.30
Std. Dev.	4.67	16.08	4.09	11.66

Source: Ezenics

Figure 9: Sensor Deviation from Actual - Outdoor Sensors



Source: Ezenics

Outdoor sensor results showed that, when compared with indoor results, the values of the sensor deviation from the instrument are higher. The median metric should not be overlooked since these are outdoor sensors, which typically experience a wider range of values than indoor sensors. The value of the median metric is that it better displays the trend of the results as it is not affected by high differences from actual. Even if there are only a small number of results that deviate highly from actual, the average metric can be skewed significantly.

It was found that the distance of a weather station from a location can have a significant impact on the validity of the sensor readings. In response to this, Ezenics must account for the distance the weather station is from the location, as well as any significant bodies of water that may be close to the weather station. If a weather station is not available within acceptable boundaries, the client's weather sensors should be examined for potential use within analytics.

Understanding sensor quality is important as these sensor readings are primary inputs to many AFDDI applications. Close analysis of the sensor data revealed that the average value of sensor readings is relatively close to the actual value, but the standard deviation is higher than one might consider ideal. However, because many of the AFDDI applications rely on changes in temperature or relative humidity, the accuracy of the reading is less important than if we were relying on the nominal sensor value. This method is deemed usable if on-site validation proves that the faults Ezenics detected are accurate.

Faults 5.3.2

The following table displays the summary of control faults and their validation results. The takeaways Ezenics took from these validations are explained in further detail in Task 5.3 - Report on Manual Proof of Concept Implementation Results.

Table 17: Control Faults Summary - On-site Validation

Fault	System	Results	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Store Hours	HVAC	9	n/a	9	BMS Analysis	9	100%
HVAC Schedules	HVAC	462	$10,430	462	BMS Analysis	462	100%
Cooling/ Heating Setpoint	HVAC	680	$6,970	680	BMS Analysis	680	100%
Economizer Damper Excessive Rate of Change/ Hunting/Cycling	HVAC	336	n/a	336	BMS Analysis	336	100%
No Communication	HVAC	24	n/a	10	On-site Validation	10	100%
Improper Cooling Staging: Multiple Stages Starting Simultaneously and Short Delay Between Stages	HVAC	377	n/a	376	BMS Analysis	376	100%
Setpoint Not Met - ZAT - Over Cooling - Occupied/Unoccupied	HVAC	35	$33,006	35	BMS Analysis	35	100%
ZAT Drift: Cooling Not Activated - Occupied/Unoccupied	HVAC	17	n/a	16	BMS Analysis	16	100%
ZAT Drift: Heating Not Activated -	HVAC	17	n/a	17	BMS Analysis	17	100%

Fault	System	Results	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Occupied/Unoccupied							
Command vs. Status Mismatch - Lights Off	Lighting	11	n/a	11	BMS Analysis	11	100%
Command vs. Status Mismatch - Lights On; Deactivation of Sales Floor Lights Delayed; and Sales Floor Lights Reactivated Too Early	Lighting	19	$61,410	19	BMS Analysis	19	100%
HOA Switch: Manual Mode	Lighting	8	n/a	8	BMS Analysis	8	100%

Source: Ezenics

The following table displays the summary of mechanical faults and their validation results. The takeaways Ezenics took from these validations are explained in further detail in Task 5.3 - Report on Manual Proof of Concept Implementation Results, Appendix A.

Table 18: Mechanical Faults Summary - On-site Validation

Fault	System	# of Machines with Fault	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Return Air Temperature Sensor Failure: Unexpected Value[1]	HVAC	12	n/a	7	BMS Analysis/On-site validation	1	14%
Supply Air Temperature Sensor Failure: Unexpected Value[2]	HVAC	23	n/a	2	On-site Validation	1	50%
Zone Air Relative Humidity Sensor Failure: Unexpected Value	HVAC	19	n/a	2	On-site Validation	2	100%

Fault	System	# of Machines with Fault	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Zone Air Temperature Sensor Failure: Unexpected Value	HVAC	13	n/a	4	On-site Validation	4	100%
Cooling Low Efficiency (Stage(s) #, #, #, #)– Steady State[3]	HVAC	115	n/a	57	On-site Validation	50	88%
Cooling Stage # Failure – Startup[3]	HVAC	237	n/a	69	On-site Validation	56	81%
Cooling Stage # Cycling[3]	HVAC	378	n/a	35	On-site Validation	29	83%
Heating Low Efficiency (Stage(s) #, #, #, #) - Steady State	HVAC	14	n/a	5	On-site Validation	5	100%
Heating Stage # Failure – Startup[3]	HVAC	33	n/a	6	On-site Validation	5	83%
Heating Stage # Cycling	HVAC	176	n/a	10	On-site Validation	10	100%
Setpoint Not Met - ZAT - Under Cooling - Occupied/Unoccupied	HVAC	119	n/a	56	On-site Validation	49	88%
Setpoint Not Met - ZAT - Under Heating - Occupied/Unoccupied	HVAC	21	n/a	7	On-site Validation	7	100%
Supply Air Fan Cycling	HVAC	408	n/a	16	On-site Validation	16	100%

Source: Ezenics

1. It was found that when the fan turned off, the hot plenum air was moving back through the unit causing a higher than expected temperature.
2. There was a unit that was supplying 150 degrees as a result of extreme stratification in a refrigerated area
3. After reviewing the results, tuning was performed on units with multiple compressors to ensure no false positives were thrown.

No Faults 5.3.3

During the on-site validation efforts, Ezenics also had KEC investigate machines that the Ezenics platform was not generating faults for. The purpose of this exercise was to ensure any issues that were occurring on the machine but that were not being diagnosed by the AFDDI platform are caught by the platform in the future. The necessary changes or additions to formulas would be made to increase the breadth and dependability of the formula library.

Table 19: No Faults Summary - On-site Validation

	System	# of Machines with Fault	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
No Faults	HVAC	7	0	7	On-site Validation	7	100%

Source: Ezenics

Results 5.3.4

While sensors are not perfect in terms of their nominal sensor value, they can still be used to identify problems with a high level of accuracy and precision as shown in the on-site validation results. Results also revealed that there is a huge opportunity in identifying and repairing control issues that result in both comfort and energy problems with a quick return on investment. Mechanical failures, which are more difficult to detect and costly to repair, were also identified with a high level of success proving the validity and effectiveness of using AFDDI to decrease energy demand and consumption. The takeaways from this field study provide for changes to be made to improve the accuracy of formulas as the project advances to the 252 location deployment phase.

Formula Selection 5.4

Algorithms are the end game of the entire setup process and are the foundation for the definition of AFDDI. There are many types of equipment within the supermarket environment. As a result, there are many different types of algorithms that can be applied, some that are unique to the specific type of equipment based on that equipment's characteristics. Ezenics has an algorithm library that is flexible, ever growing, and improving. In Table 20, the fault categories that can be detected are shown for each machine type. The machine types are then grouped into machine categories in the table as well.

Table 20: Fault Detection Categories by Machine Type

Machine Category	Machine Type	Fault Detection Categories
HVAC	Air Handling Unit	Air flow
		Controller
		Cooling
		Dehumidification
		Economizing
		Fan
		Heating
		Outside Air Damper
		Scheduling
		Sensor
		Setpoint
	Constant Volume Air Terminal Unit	Controller
		Cooling
		Damper or Air flow
		Heating
		Scheduling
		Sensor
		Setpoint
	Fan Coil Unit	Controller
		Cooling
		Fan
		Heating
		Scheduling
		Sensor
		Setpoint
	Fan Powered Air	Controller

Machine Category	**Machine Type**	**Fault Detection Categories**
	Terminal Unit	Cooling
		Damper or Air flow
		Fan
		Heating
		Scheduling
		Sensor
		Setpoint
	Rooftop Unit	Air flow
		Controller
		Cooling
		Dehumidification
		Economizing
		Fan
		Heating
		Outside Air Damper
		Scheduling
		Sensor
		Setpoint
	Variable Volume Air Terminal Unit	Controller
		Cooling
		Damper or Air flow
		Heating
		Scheduling
		Sensor
		Setpoint
HVAC/Refrigeration	Global Machine	Controller
		Dehumidification
		Economizing
		Scheduling
		Sensor
Lighting	Lighting Machines	Contactor/Relay
		Controller
		Manual Switch Overrides
		Scheduling
		Sensor

Machine Category	Machine Type	Fault Detection Categories
Power Meter	Power Meter	Controller
		Energy
		Loading
		Sensor
Refrigeration	Refrigeration	Controller
		Cooling
		Defrost
		Dehumidification
		Fan
		Heating
		Sensor
		Setpoint
Weather	Weather Station	Controller
		Sensor

Source: Ezenics

Ezenics has developed a guiding tool called the "template selection tool" to aid in the formula identification process. The main benefits the tool provides are identification of formulas and formula implementation tracking. By inputting the mapping set and the machine parameters, the tool can identify all of the possible formulas that can be applied to the equipment on the mapping set. This functionality is valuable because formulas can accidently be looked as there are many that can be applied. Once a formula is implemented on the Ezenics system, it can be tracked in the template selection tool. Manually input formulas can also be tracked in the template selection tool. Details on how algorithms are implemented are in the next section.

Formula Implementation 5.5

After formulas have been identified by the template selection tool, it is time to implement the formulas to the client machines setup in the Ezenics system. The primary tool to use in the Ezenics system is the “diagnostics settings tool”. To fully understand the capability of the diagnostics settings tool, the structure of the algorithms must be discussed.

Each formula is a series of steps, the logic, which takes inputs and provides a fault output, a calculated value output, or both depending on the purpose of the formula. For each formula, any number of templates can be created. Templates act as different sets of inputs for the logic of the formula. The flexibility of the templates allows for one formula to be applied to many different types of equipment, instead of having to use a different formula for each type of equipment.

The diagnostics settings tool requires three inputs: the machines, the formula, and the template. Within each template selected, there are inputs and thresholds to utilize in the formula calculation. Standard templates are built into the system for quick implementation once the template selection tool identifies a formula. Non-standard templates are developed from standard templates when certain points are unavailable but alternate points may be used. An example of a non-standard template is when a standard template that typically uses a cooling stage command is adjusted to use the cooling stage status because the command point is unavailable.

Once a formula and template are implemented on the selected machines, the system automatically calculates the formula. The incoming data are continually processed as time progresses so that results are constantly up to date.

The next stage is formula verification. The purpose of this step is to ensure the applied formulas are generating faults when they should be and not generating faults when they should not be. This step acts as a double check to both the storage validation step and the template selection tool formula identification because those two items can be the cause of the issues with formula results. Formula verification involves running results reports, graphing data, and checking mapping sets for proper labels and conversions. This step also often involves using machine graphics or drawings so that what results are and are not generated are appropriate.

The final quality assurance procedure on the analytics side of the process is formula error correction. Due to how the analytics are implemented, there are a number of ways that a formula error can be generated. The process of correcting formula errors acts as another step in the process to ensure that the algorithms are operating as expected and providing current results.

The combination of all of the tools and processes that Ezenics has developed provides for a robust, efficient, and rapid method for setting up smart supermarkets. Ezenics strives to provide accurate, useful results to clients without need for hardware installation or a cumbersome setup process.

Results 5.6

The following tables show the breakdown of work that was completed each month during the setup process. These times listed are for one employee's working on the project for 40 hours per week. Many of the tasks can be done in parallel so if more resources were available, the timeline would shorten. The three main categories of equipment discussed are refrigeration, HVAC, and lighting. The HVAC and lighting equipment are setup simultaneously. Refrigeration and HVAC share many of the same tasks.

First, equipment questionnaires are filled out. The equipment information is used in assigning formulas and determining the financial impact of a fault. For refrigeration equipment, the equipment surveys are filled out as part of an automated process. Next, tickets are made as part of the managerial tasks and sent to a support team who sets up the machines in the Ezenics system and configures the data storage. Third, the data storage is examined in the storage monitor where any errors are addressed and corrected and the stored points are validated. Fourth, after the storage errors are corrected, the FDD formulas are applied. After the formulas have run, any formula implementation errors caught by the system are corrected. Lastly, after the formula errors are addressed, the formulas are validated to confirm that the inputs and outputs are correct, that results are output when they should be, and results are not output when they should not be.

Table 21: HVAC and Lighting Monthly Task Breakdown – One Worker

Task	Required Work Days
Managerial Tasks	2
Equipment Survey	5
Data Storage Setup	5
Data Storage Error Correction	2
FDD Setup	5
FDD Validation	2
FDD Wrap Up	2
Total	23

Source: Ezenics

Table 22: Refrigeration Monthly Task Breakdown – One Worker

Task	Required Work Days
Managerial Tasks	5
Data Storage Setup	10
Data Storage Error Correction	3
FDD Setup	3
FDD Wrap Up	2
Total	23

Source: Ezenics

The following tables show the monthly setup numbers for the refrigeration and the HVAC/lighting systems. The refrigeration machines for each location are typically setup at an average of 80 locations per month. The HVAC/lighting machines for each location are typically setup at an average of 45 locations per month. The refrigeration equipment can be setup faster because of the BMS it utilizes. It is simpler to pull information from the refrigeration BMS, which makes partial automation possible. With the HVAC/lighting BMS, everything is essentially manual in the equipment survey and setup process.

Table 23: Refrigeration Setup Timeline

Month	# of Data Storage Setups	# of AFDDI Setups
1	101	92
2	98	90
3	51	68
4	0	0
5	0	0
6	0	0
Total	250	250

Source: Ezenics

Table 24: HVAC and Lighting Setup Timeline

Month	# of Data Storage Setups	# of AFDDI Setups
1	42	42
2	48	48
3	45	45
4	30	30
5	60	60
6	25	25
Total	250	250

Source: Ezenics

The California retail locations varied in terms of size, age, equipment, and technology. The data exchange carrier and AFDDI algorithms are designed to handle all of these variables. The following statistics are provided to display the flexibility of the platform as a whole.

The locations range in floor area from 80,000 to 215,000 square feet. The total square footage for all 252 locations is approximately 33,000,000 square feet. The construction dates of the buildings range from two to 30 years ago. In the following table the variety of equipment manufacturers is presented. Lighting manufacturers are not included.

Table 25: Equipment Brands in the 252 CA Locations

HVAC	Refrigeration
Aaon	Hussmann
Carrier	Tyler
Lennox	Hill Phoenix
Munters	Barker
Seasons 4	Floraline
Trane	Zero Zone

Source: Ezenics

In the following two tables, the counts of each equipment type are provided. The first table displays the equipment counts by type of machine, such as RTUs or refrigeration cases. Power meters are included here as they were involved in some of the analytics applied to the machines. The second table shows overall counts for each major equipment category including HVAC, refrigeration, and lighting.

Table 26: Summary of Equipment by Machine Type

Machine Type	Count
Air Handling Unit (AHU)	20
Fan Coil Unit (FCU)	23
Single Zone Rooftop Unit (RTU)	3,818
RTU with Dehumidification (RTUD)	302
Air Terminal Unit (ATU)	1,468
Unit Heater (UH)	31
Variable Air Volume (VAV) RTU	183
Utility Meter(s)	276
Sub-meters	4,112
Refrigeration Cases	4,046
Refrigeration Compressors	298
Refrigeration Anti-sweat Heaters	143
Refrigeration Condensers	255
Lighting	1,253
Weather	252

Source: Ezenics

Table 27: Equipment Count by Equipment Category

Type	Count	Comments
HVAC	5,845	Includes AHUs, FCUs, RTUs, RTUDs, ATUs, and UHs; 3 to 50 Tons
Lighting	1,253	Includes sales floor, parking, and miscellaneous lighting
Refrigeration	4,742	Includes cases, compressors, anti-sweat heaters, and condensers

Source: Ezenics

After all of the formulas for the various equipment were validated, their outputs were examined. The results are displayed in the following section.

HVAC Results 5.6.1

HVAC is the foundation of the Ezenics platform and is the most advanced of any of the analytics that Ezenics offers. The control faults that were checked were heating setpoints, cooling setpoints, and schedules. It is suggested that a client examine and correct the control faults before the mechanical faults because a mechanical fault may be occurring due to an incorrect control point. Furthermore, control faults are very simple to validate: a user looks at the building operation specifications and the control point in the BMS. The financial impact is calculated based off of the size of the unit, annual run time, site energy rates, and local weather patterns.

Table 28: HVAC Control Fault Results[1,2]

Problem	# of Issues	Avg. # of Issues per Machine	Projected Yearly Cost (kW)	Projected Yearly Cost (kWh)
Cooling Setpoint (Occupied)	2,039	0.34	$42,376	$330,891
Cooling Setpoint (Unoccupied)	689	0.12		$31,003
Heating Setpoint (Occupied)	1,856	0.31	-	-
Heating Setpoint (Unoccupied)	823	0.14	-	-
HVAC Schedule (Occupied)	1,738	0.29	-	$33,064
HVAC Schedule (Unoccupied)	2,028	0.34	-	$242,488
HVAC Total	9,173	1.54	$42,376	$637,448

1. 252 Locations (5845 HVAC) in the sample.
2. Projected Yearly Cost is based on local weather patterns and local utility rates.

Source: Ezenics

The mechanical faults that were checked across the 252 CA locations are shown in Table 29. The faults generated for the 252 locations produced a projected annual impact of $1,639,568 across 13,926 issues with an average of 3.21 issues per unit.

Table 29: HVAC Mechanical Fault Results[1]

Problem	# of Issues	Avg. # of Issues per Machine	Projected Yearly Cost (kW)	Projected Yearly Cost (kWh)
Non-optimized Econ Settings	4,374	1.01	-	$321,005
Outdoor Air Temperature Sensor	3,550	0.82	-	$588,682
Simultaneous Heating/Cooling	50	0.01	-	$36,307
Cooling Stage Failure	650	0.15	-	$57,941
Econ Damper Compromised	625	0.14	-	$165,544
Actual OA Ratio Above Minimum	1650	0.38	-	$404,663
Heating/Cooling Stage Cycling	183	0.04	-	$98
Fan Cycling	2,795	0.65	-	$13,953
Indoor Relative Humidity (RH) Sensor[2]	27	0.11	-	$12,854
ERV Wheel Inefficiency[3]	22	0.07	$8,989	$38,521
Total	13,926	3.21[4]	$8,989	$1,639,568

1. 252 Locations (4021 RTUs/302 RTUDs) in the sample.
2. Only one indoor RH sensor per site.
3. Only for RTUs with sensible wheels.
4. Does not include Indoor RH Sensor and ERV Wheel Inefficiency results.

Source: Ezenics

Refrigeration Results 5.6.2

Refrigeration control points are closely monitored for the 252 locations. The most important points to monitor are the suction pressure, head pressure, temperature, alarm setpoints, defrost settings, and the anti-sweat heater control points. The suction and head pressures control the compressor operation. The temperature setpoint controls what temperature the case will try to maintain. The alarm thresholds are the temperatures and times at which an alarm will be generated and sent to a response team. The defrost parameters dictate how long the defrost lasts and what the termination temperature is. Finally, the anti-sweat heater parameters determine how much energy the system will output in order to warm up the glass.

Table 30: Refrigeration Fault Results

Problem	# of Issues	Avg. # of Issues per Machine	Projected Yearly Cost (kW)	Projected Yearly Cost (kWh)
Suction Pressure[2]	114	0.57	-	$14,127
Head Pressure[3]	20	0.08	-	$4,719
Temperature Setpoints	706	0.17	-	$34,819
Alarms	1,565	0.39	-	-
Defrost	1,797	0.44	-	-
Anti-sweat Heater[1]	42	0.29	-	$32,098
Total	4,068[4]	1.00[4]	$0	$85,763

1. Anti-sweat heaters affect all glass door cases at a location.
2. Only applies to suction machines.
3. Only applies to condenser machines.
4. Does not include anti-sweat heater, suction, or condenser machine results.

Source: Ezenics

Lighting Results 5.6.3

Lighting issues are some of most common and the most costly. For example, if a retail location has a special occasion, such as opening early the day after Thanksgiving, the lights may be reprogrammed to turn on 1 to 6 hours earlier than normal. If that change is forgotten, the lights will continue to turn on 1 to 6 hours early every day, which could end up costing the store thousands of dollars over the course of a year. All of the summary results can be found in Table 31.

Table 31: Lighting Fault Results

Problem	# of Issues	Avg. # of Issues per Machine	Projected Yearly Cost (kW)	Projected Yearly Cost (kWh)
Deactivation of Sales Floor Lights Delayed	85	0.07	-	$392,730
Sales Floor Lights On Too Early	76	0.06	-	$193,966
Sales - Command vs. Status Mismatch - Lights On	250	0.20	-	$789,256
Total	411	0.33	$0	$1,375,952

Source: Ezenics

Total Results 5.6.4

The overall purpose of this project was to build credibility for the smart technologies, to further the Title 24 code, and to advance adoption of their program and the successful, beneficial technologies contained therein. Information regarding the speed of setup and the results of the setup are included in this report. The benefits of the technology are the primary focus of the report, so that the smart technologies can be applied to other retail buildings of various ages and potentially other commercial building facilities. The financial and comfort benefits of the Ezenics AFDDI platform have been demonstrated in this deliverable and are applicable to buildings of all shapes and sizes.

Altogether the Ezenics AFDDI platform identified 27,754 issues across 252 locations for a whopping 111 issues per location, average and a total calculated yearly cost of $3,790,096. Furthermore, many of the issues, especially the control issues, could be fixed quickly and remotely, which means there is no cost to roll a truck or replace a piece of equipment.

Table 32: Issue Summary

Category	# of Issues	Projected Yearly Cost (kW + kWh)
Control	13,828	$2,141,539
Mechanical	13,926	$1,648,557
Total	27,754	$3,790,096

Source: Ezenics

The Ezenics platform can detect issues accurately and display them in an efficient way; however, the true value is lost upon inaction. The maximum value of the tool will only be realized when clients act on the results that are generated in a financially responsible manner. Sending a technician to fix a cooling coil on one RTU may not make sense financially for the company because the other RTUs are oversized and can handle the additional load. With the monetary impact generated within the Ezenics AFDDI platform, a company can minimize their financial investment and maximize their energy savings and building comfort.

CHAPTER 6:
Conclusion

The goal of this project was to develop, demonstrate, deploy, and evaluate near-zero-cost, non-invasive, plug-n-play diagnostics and optimization technologies that can be adopted by both existing and new buildings immediately. The objectives were to:

1. Develop a data exchange carrier on a scalable infrastructure that can establish connectivity with an unlimited number of building automation systems to obtain, calibrate, store, and process data at a near-zero-cost manner.
2. Develop five low-cost virtual sensors that can expand the onboard measurements and enable existing and new diagnostics and optimization technologies.
3. Develop multiple-system based diagnostics and optimization technologies that address the interactions among different systems of the same type and different types of systems in buildings.
4. Integrate existing and new technologies into an enterprise plug-n-play diagnostics and optimization solution for enabling smart buildings thatcan be deployed in a non-invasive and near-zero-cost manner.
5. Deploy, evaluate, and demonstrate the enterprise plug-n-play diagnostics and optimization solution in 252 supermarket stores in California.

A data exchange carrier was created in the cloud, which makes it scalable and affordable. The data exchange carrier can collect data from 16 different protocols. The data exchange carrier is currently collecting 555,200 data points continuously from the 252 locations across 5,845 HVAC machines, 1,253 lighting machines, and 4,742 refrigeration machines.

Five virtual sensors were created. The five virtual sensors that were created are: supply air flow, refrigerant charge, cooling capacity, mixed air temperature, and energy efficiency ratio. Virtual sensors calculate outputs by analyzing physical conditions in which multiple thermodynamic properties can be utilized to gain additional information. One example of this situation is a mixed air temperature sensor. A mixed air temperature sensor measures the air temperature before the cooling and heating coils. A supply air temperature sensor measures the air temperature after the cooling and heating coils and is typically available on an RTU. If the mixed air temperature and the supply air temperature are known, the efficiency and operation of the heating and cooling coils can be continuously checked through the use of an FDD algorithm. The virtual sensors enable remote sensor calibration and expand the list of FDD algorithms that can be applied to equipment.

While studying the indoor environment, it was found that zone humidity is a point of interaction between the HVAC and refrigeration systems. By lowering the humidity via the HVAC system, a net energy savings can be achieved due to the reduced energy consumption of the refrigeration system. The humidity should be lowered to a point where it takes more HVAC energy to lower the humidity than is saved by the refrigeration system. Additionally, by using sensor data from nearby weather stations, it was possible to check the outdoor air temperature sensors used by the rooftop units. Frequently the outdoor air temperature sensor used by the rooftop units was located in a position such that it was heavily influenced by direct sunlight. As a result the economizing of the rooftop units was heavily under-utilized, which means excess energy is being consumed. Only an external system that is checking and comparing programmed schedules and setpoints to their intended guidelines can detect these types of issues.

The Ezenics AFDDI system collects and stores data on the cloud and, as a result, the FDD algorithms can be applied within the cloud. Therefore, no additional resources are drained from the clients building management system. To view the FDD results a client runs an online report from the Ezenics website. This web-based report ensures that no matter how many disparate building management systems the client is using, the interface for all of them will be the same within the Ezenics platform.

The data exchange carrier, virtual sensors, and automated FDD algorithms were deployed to 252 commercial retail buildings throughout California, covering over 33,000,000 square feet. The 252 locations contained over 11,800 different pieces of equipment. The FDD algorithms were implemented on all of the machines and the FDD algorithms identified 27,754 issues for a total of $3,790,096 in calculated savings.

Glossary

Acronym	Definition
AFDDI	Automated Fault Detection, Diagnostics, and Impact
AHU	Air Handling Unit
ALC	Automated Logic Corporation
Amazon EC2	Amazon Elastic Compute Cloud
ATU	Air Terminal Unit
BMS	Building Management System
CA	California
Energy Commission	California Energy Commission
DDC	Direct Digital Control
EER	Energy Efficiency Ratio
FCU	Fan Coil Unit
FDD	Fault Detection and Diagnostics
GQL	Graphical Query Language
HVAC	Heating, Ventilation, and Air Conditioning
HVAC&R	Heating, Ventilation, and Air Conditioning and Refrigeration
IaaS	Infrastructure as a Service
IP	Internet Protocol
IT	Information Technology
KEC	Katin Engineering Consulting
kW	Kilowatts
kWh	Kilowatt Hour
MA	Mixed Air
MS	Microsoft
MSCT	Mapping Set Creation Tool
NBI	New Buildings Institute
OARH	Outside Air Relative Humidity
OAT	Outside Air Temperature
PCA	Principle Component Analysis
PGE	Pacific Gas and Electric
RAT	Return Air Temperature
RH	Relative Humidity
RTU	Rooftop Unit
RTUD	Rooftop Unit with Dehumidification
SA	Supply Air
SAT	Supply Air Temperature
SCE	Southern California Edison
SDGE	San Diego Gas and Electric
SLA	Service Level Agreement
SQL	Structured Query Language
UH	Unit Heater
VAV	Variable Air Volume
VMAT	Virtual Mixed Air Temperature
VMATwb	Virtual Mixed Air Wet Bulb Temperature
VOAR	Virtual Outdoor Air Ratio

VPN	Virtual Private Network
ZARH	Zone Air Relative Humidity
ZAT	Zone Air Temperature

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APPENDIX A:

Report on Manual Proof of Concept Implementation Results

Agreement # 500-08-050

ENTERPRISE PLUG-N-PLAY DIAGNOSTICS AND OPTIMIZATION FOR SMART BUILDINGS

5.0 – Smart Supermarket

Task 5.3 – Demonstration Preparation

Deliverable – Report on Manual Proof of Concept Implementation Results

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Energy Efficiency Research Office
Buildings End-Use Energy Efficiency
State of California
California Energy Commission

Goal

An optimized setup and implementation process is required to perform accurate analytics entailing machine characteristics, quality data, normalization of data, analytic implementation, and analytic validation.

The goal of the Report on Manual Proof of Concept Implementation Results is to perform manual ‘offline’ validation to determine if any modifications and fine tuning are necessary before implementation across the entire portfolio of locations.

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1. INTRODUCTION

In an effort to test and fine-tune accuracies of the technologies prior to implementation of the entire California portfolio, a number of locations were chosen for on-site validation of the fault detection and diagnostic (FDD) results. Bob Katin of Katin Engineering Consultants (KEC) performed the on-site validations with the support of Ezenics offsite. Upon completion of the visits, results were analyzed and a report was completed.

2. METHODOLOGY

2.1 LOCATION SELECTION

Locations, shown in Table 1, were selected based on the following criteria to ensure that a wide variety of faults could be validated to maximize the value of the on-site visits:

- Located within Investor-Owned Utility (IOU) territory.
- Diverse number of CEC climate zones.
- Variety of fault diagnostics.

Table 1 - Selected Locations

Store #	Location (City)	# of Machines	IOU	CEC Climate Zone
30	Modesto	22	-	12
52	Sacramento Riverside	23	-	12
64	Dublin	18	PG&E	12
67	Pittsburg	39	PG&E	12
96	Modesto NW	25	-	12
100	San Ramon	24	PG&E	12
103	Napa	23	PG&E	2
140	Fresno	24	PG&E	13
147	San Jose Capitol	27	PG&E	4
148	San Jose Westgate	28	PG&E	4
149	San Leandro Bayfair	30	PG&E	3
150	Napa North	21	PG&E	2
154	Richmond	25	PG&E	3
156	Sacramento SW	26	-	12
162	Antioch Slatten Ranch	33	PG&E	12
173	San Jose	21	PG&E	4
178	San Jose Story Road	28	PG&E	4
186	San Jose College Park	30	PG&E	4
187	Riverbank	27	-	12
200	San Jose East	22	PG&E	4
204	West Sacramento	28	PG&E	12
208	San Jose Central	29	PG&E	4
216	Lathrop	28	PG&E	12
237	Sacramento East	31	-	12

These locations were setup using the process defined in the previous deliverable “Diagnostic and Optimization Schedule”. The FDD results were evaluated and placed into this report for on-site validation.

2.2 MANUAL VALIDATION

The goal of the on-site validation was to confirm the accuracy of sensors for the use of the fault detection, the validity of the algorithms, identify undetected faults for further analytic development, and the gathering of data for the development of virtual sensors.

2.2.1 SENSOR ACCURACY

Sensor validity for the use of AFDDI was examined by taking on-site measurements at a number of machines. The sensors that were tested and their descriptions are listed below:

- Supply Air Temperature (SAT) - validated by measuring the temperature at the diffuser outlets on selected machines under a variety of system configurations (economizing, minimum damper position, and different number of cooling stages on).
- Zone Air Temperature (ZAT) – measurements were taken near the zone temperature/humidity thermostat within certain zones throughout the store.
- Zone Air Relative Humidity (ZARH) - measurements were taken near the zone temperature/humidity thermostat within certain zones throughout the store.
- Return Air Temperature (RAT) – measurements were taken in the return plenum or at the return grill of ducted systems depending on system design.
- Outdoor Air Temperature (OAT) & Outdoor Air Relative Humidity (OARH) – an attempt was made to find the OAT and OARH sensors at the store (not always successful) to compare the instrument reading to the store sensor. If the store sensor could not be found, measurements were taken at the north side of the building.

2.2.2 ALGORITHM VALIDITY

Ezenics’ algorithms were validated using two different methods depending on the type of fault that was being detected. Many faults are caused simply by control programming errors or sub-optimal control strategies. These faults could be verified simply by looking to the client’s Building Management System (BMS). Faults such as mismatched temperature setpoints and schedules between machine and business rule fall into this category.

The detection of mechanical component failures or maintenance issues causing component inefficiency must be validated on-site. Faults such as heating/cooling stage inefficiencies fall into this category. Worksheets were created containing the faults that Ezenics detected for KEC to verify on-site.

2.2.3 UNDETECTED FAULTS

An additional task that KEC performed on-site was to look for faults that Ezenics did not detect. Any issues that were undetected by Ezenics but found during on-site validation by KEC would be used to help Ezenics develop new faults or determine if a current fault needed to be adjusted. This process helps improve the accuracy of the analytics.

2.2.4 DATA GATHERING FOR VIRTUAL SENSORS

Various data were gathered to aid in the development and validation of virtual sensors. The virtual sensor results are covered in the Field Evaluation Report deliverables of tasks 3.2 and 3.3.

3. RESULTS

3.1 SENSOR CALIBRATION

Indoor sensor results revealed that the sensor deviation from the instrument is relatively small when observing the average deviation of the sensor from the actual. The results shown in Table 2 and Figure 1 also show that significant deviations from the actual values do exist even though the average value of similar sensor types may lie close to the actual. For example, out of 61 return air temperature (RAT) sensor readings taken, the average deviation from the actual was 1.93°F and the standard deviation from this average was ±2.19°F. The average value of 1.93°F is excellent in terms of portraying the reliability of the sensors, but a standard deviation value of ±2.19°F shows that the sensor values composing that average varied significantly.

Table 2 - Indoor Sensor Validation Results

	RAT	SAT	ZAT	ZARH
N	61	147	141	47
Average	1.93	2.34	1.74	5.45
Median	1.10	1.60	1.30	4.50
Min	0.00	0.00	0.00	0.30
Max	10.40	11.10	7.10	16.40
Std Dev	2.19	2.41	1.41	3.68

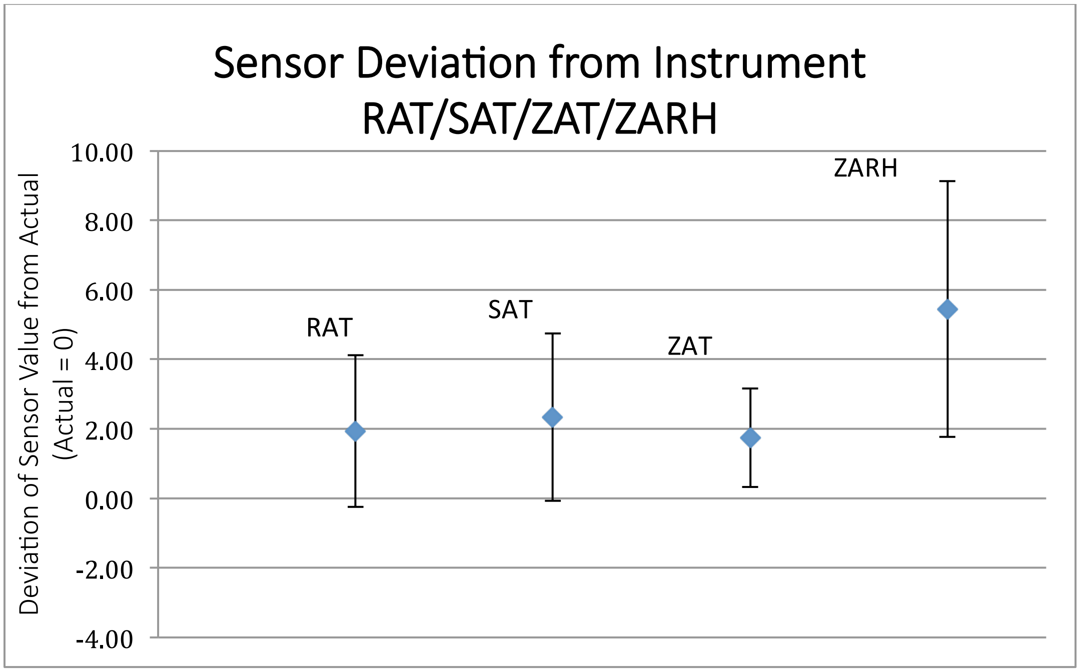

Figure 1 - Sensor Deviation from Actual: Indoor Sensors

Two sets of outdoor sensors were compared to the instrument sensor reading: (1) the client's Global machine which broadcasts to the other machines at the location and (2) Ezenics' weather station data. When possible, the instrument sensor readings were taken multiple times at each location, throughout different times of the day. As a result, there were approximately 60 sets of data to compare with the Global machine and Ezenics' weather machine. The results can be seen in Table 3 and Figure 2.

Table 3 - Outdoor Sensor Validation Results

	Global Machine		Weather Station	
	OAT	OARH	OAT	OARH
N	61	60	61	57
Average	5.68	14.19	6.00	16.41
Median	4.25	6.15	5.10	13.80
Min	0.10	0.30	0.20	0.40
Max	18.90	72.90	17.40	45.30
Std Dev	4.67	16.08	4.09	11.66

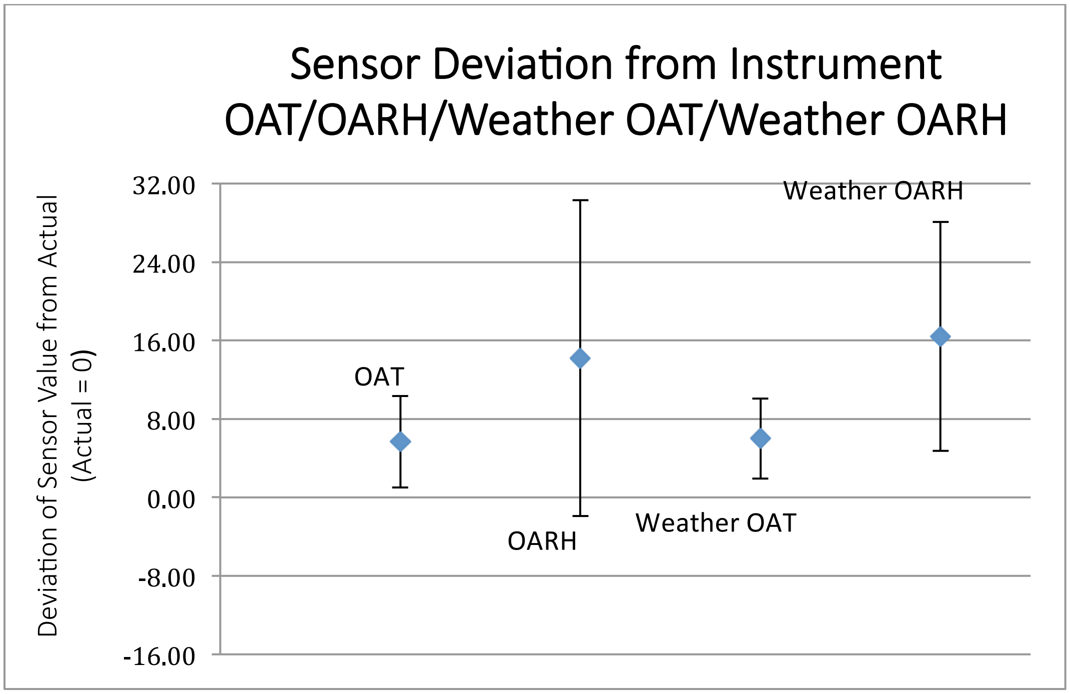

Figure 2 - Sensor Deviation from Actual: Outdoor Sensors

Outdoor sensor results showed that, when compared with indoor results, the values of the sensor deviation from the instrument are higher. The median metric should not be overlooked since these are outdoor sensors, which typically experience a wider range of values than indoor sensors. The value of the median metric is that it better displays the trend of the results as it is not affected by high differences from actual. Even if there are only a small amount of results that are high differences from actual, the average metric can be skewed significantly.

When comparing the client's Global machine to the weather station data used by Ezenics, it was found that the averages for all sensors were comparable between the two, but the median values varied significantly for the outdoor air relative humidity (OARH) sensor. However, the client's Global machine experienced higher maximum values and standard deviations. The explanation for this situation is that the weather data used by Ezenics had more data that was in the middle of the range of values, while the client's Global machine had greater range of data, but the extremes had a smaller frequency than the extremes on the weather machines.

Looking at environmental conditions, while Ezenics attempts to gather data from the closest weather station to the location, the client's Global machine which measures temperature and humidity, is on site. Additionally, the presence of various bodies of water near the examined locations influences the temperature and relative humidity measurements. This condition is especially evident in the case of the OARH sensor, as the outdoor air temperature (OAT) sensor average and median metrics were close in value for the Global machine and weather station. However, even the OARH at the Global machine on site experienced significant differences from the instrument readings, indicating that the client's on site OARH sensors vary significantly.

It was found that the distance of a weather station used by Ezenics from a location can have a significant impact on the validity of the sensor readings. In response to this, Ezenics must account for the distance the weather station is from the location, as well as the weather station's any significant bodies of water that may be close to the weather station. If a weather station is not available within acceptable boundaries, the client's weather sensors should be examined for potential use within analytics.

Understanding sensor quality is important as these sensor readings are primary inputs to many automated fault detection diagnostics and impact (AFDDI) applications. Close analysis of the sensor data revealed that the average value of sensor readings is relatively close to the actual value, but the standard deviation is higher than one might consider ideal. However, because many of the AFDDI applications rely on changes in temperature (or RH), the accuracy of the reading is less important than if we were relying on the nominal sensor value. This method is deemed usable if on-site validation proves that the faults Ezenics detected are accurate.

3.2 AUTOMATED FAULT DETECTION DIAGNOSTICS

Total faults occurring at each location can be broken down into two main groups: those caused by control issues and those caused by mechanical failures. A summary of the results from the four locations can be seen in Table 4. These issues can occur on HVAC, Lighting, and Refrigeration machines.

Table 4 - Total Faults Occurring at Validation Stores

Issue Category	# of Faults	Financial Impact
Control	2379	$114,589
Mechanical	2550	$0.00

3.2.1 CONTROL FAULTS

Faults are identified as 'Control' faults as they are caused by either sub-optimal control strategies or setpoint/schedule deviations from the client's operative guidelines. An example of a setpoint deviation would be a cooling setpoint that is 2°F lower than the client's desired setpoint. While the lower setpoint will likely never cause a problem with the RTU other than slightly shortening the equipment's lifespan as a result of increased runtimes, it will certainly consume a significantly increased amount of energy as a result. Table 5 below contains a summary of the control faults for all locations.

Table 5 - Control Faults Summary

Fault	System	Results	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Store Hours	HVAC	9	$0.00	9	BMS Analysis	9	100%
HVAC Schedules	HVAC	462	$10,430	462	BMS Analysis	462	100%
Cooling/ Heating Setpoint	HVAC	680	$6,970	680	BMS Analysis	680	100%
Economizer Damper Excessive Rate of Change/ Hunting/Cycling	HVAC	336	$0	336	BMS Analysis	336	100%
No Communication	HVAC	24	$0	10	On-site Validation	10	100%
Improper Cooling Staging: Multiple	HVAC	377	$0	376	BMS Analysis	376	100%

Fault	System	Results	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Stages Starting Simultaneously and Short Delay Between Stages							
Setpoint Not Met - ZAT - Over Cooling - Occupied/Unoccupied	HVAC	35	$33,006	35	BMS Analysis	35	100%
ZAT Drift: Cooling Not Activated - Occupied/Unoccupied	HVAC	17	$0	16	BMS Analysis	16	100%
ZAT Drift: Heating Not Activated - Occupied/Unoccupied	HVAC	17	$0	17	BMS Analysis	17	100%
Command vs Status Mismatch - Lights Off	Lighting	11	$0	11	BMS Analysis	11	100%
Command vs Status Mismatch - Lights On; Deactivation of Sales Floor Lights Delayed; and Sales Floor Lights Reactivated Too Early	Lighting	19	$61,410	19	BMS Analysis	19	100%
HOA Switch: Manual Mode	Lighting	8	$0.00	8	BMS Analysis	8	100%

Each control fault from the table above is discussed in the following section. Each fault explanation contains the fault description, fault cause, how the fault was validated, the impact of said fault, and how the fault would be fixed. After the explanation of each fault, there is a 'takeaways' section that discusses new knowledge gained from the manual investigation of the fault.

3.2.1.1 STORE HOURS

Description: This fault occurs when the store is running on a schedule contrary to the desired schedule as dictated by the client's operational guidelines (OG).

Cause: This fault has a number of causes all related to programming. The store schedule may be adjusted for a temporary period of time as dictated by the need of occupants and sometimes will not be changed back to the desired schedule. This adjustment could cause all of the schedules of the machines in the entire store to run incorrectly for an extensive amount of time before being noticed, especially if the schedule has been set to be occupied during unoccupied hours.

Validation: The fault can be validated by looking at the client's BMS.

Impact

> *Energy* – A store schedule fault will cause additional energy consumption by all machines when the occupied hours are extended beyond the operative guidelines. Extended occupied hours allow the more stringent temperature setpoints to be in use for a longer period of time, therefore, consuming additional energy.
>
> *Comfort* – A comfort fault will occur when the occupied hours are shorter than desired. When the unit goes into unoccupied mode when the building is still in use, the zone will have a much higher cooling setpoint and much lower heating setpoint. The comfort impact on the occupants has a potential financial impact if sales drop as a result. Worker productivity could also be impacted.

How the fault is fixed: The fault can be fixed simply by making a change in the BMS. The payback period is almost instantaneous.

New Takeaways from manual investigation: None

3.2.1.2 HVAC SCHEDULES

Description: This fault occurs when the machine is running on a schedule contrary to the desired schedule as dictated by the client's operational guidelines (OG).

Cause: This fault has a number of causes all related to programming. Schedules may be adjusted for a temporary period of time as dictated by the need of occupants and sometimes will not be changed back to the desired schedule. This could cause a schedule to incorrectly run for an extensive amount of time before being noticed, especially if the schedule has been set to be occupied during unoccupied hours.

Validation: The fault can be validated by looking at the client's BMS.

Impact

> *Energy* – A schedule fault will cause additional energy consumption when the occupied hours are extended beyond the operative guidelines. Extended occupied hours allow the more stringent temperature setpoints to be in use for a longer period of time, therefore, consuming additional energy.
>
> *Comfort* – A comfort fault will occur when the occupied hours are shorter than desired. When the unit goes into unoccupied mode when the building is still in use, the zone will have a much higher cooling setpoint and much lower heating setpoint. The comfort impact on the occupants has a potential financial impact if sales drop as a result. Worker productivity could also be impacted.

How the fault is fixed: The fault can be fixed simply by making a change in the BMS. The payback period is almost instantaneous.

New Takeaways from manual investigation: None

3.2.1.3 COOLING/HEATING SETPOINT

Description: This fault occurs when the machine is running on temperature setpoints contrary to the desired setpoints as dictated by the client's operational guidelines.

Cause: This fault has a number of causes all related to programming. Setpoints may be adjusted for a temporary period of time as dictated by the need of occupants and sometimes will not be changed back to the desired setpoints. This could cause a machine to run at a more stringent setpoint for an extensive period of time before being noticed, especially if the zone comfort is unaffected.

Validation: The fault can be validated by looking at the client's BMS.

Impact

> *Energy* – A setpoint fault will cause additional energy consumption as the machine will be running at a more stringent temperature (i.e. 72°F is in use instead of the desired 74°F)
>
> *Comfort* – A comfort fault will occur when the actual setpoint is greater than the desired setpoint. The comfort impact on the occupants has a potential financial impact if sales drop as a result. Worker productivity could also be impacted.

How the fault is fixed: The fault can be fixed simply by making a change in the BMS. The payback period is almost instantaneous.

New Takeaways from manual investigation: None

3.2.1.4 ECONOMIZER DAMPER EXCESSIVE RATE OF CHANGE / HUNTING

Description: This formula checks for a rate of change in percentage open/closed of the outdoor air damper over a specified period of time. If the rate of change is higher than an allowable threshold, then the formula will diagnose that a fault has occurred.

Cause: PID variables in a control loop are not tuned properly.

Validation: The fault can be validated by looking at the client's BMS. What is causing the problem is the economizing PID loop is too constrictive. When cooling is needed during economizing times, the dampers are completely opened until the zone setpoint is met and then returned to a minimum position. This can happen during a very short period of time. The PID loop for the OA damper can be optimized to modulate to meet an SAT. This strategy would prevent the damper hunting.

Impact

> *Energy* – Could potentially cause excessive energy consumption as additional unconditioned outdoor air could be allowed into the system. Could also miss out on free cooling opportunities that would reduce the cooling load on the unit.
>
> *Comfort* – There is potential for there to be extreme fluctuation in space conditions.

How the fault is fixed: The fault can be fixed simply by making a change in the BMS. The payback period is almost instantaneous.

New Takeaways from manual investigation: There is significant opportunity for the client to optimize their economizer settings. Adjusting the economizer control would not only fix this excessive rate of change/hunting issue, but would also gain additional advantage of free cooling opportunities.

3.2.1.5 NO COMMUNICATION

Description: The formula detects if the machine controller is not communicating.

Cause: BMS system loses connection with machine. The loss of communication could be a physical failure of the control module or a loss of data connection.

Validation: On-site by KEC. Findings listed below:

- Control module on unit failed.

Impact

Energy – Could potentially cause excessive energy consumption if the unit is running under its own default parameters.

Comfort – The unit may not be running at all. This was confirmed on site by KEC.

How the fault is fixed: The fault can be fixed by replacing the control module or fixing the data connection.

New Takeaways from manual investigation: It's been somewhat unclear as to how the units perform when they are not communicating with the BMS. Finding that a unit is not running proves that comfort issues could be occurring as units in surrounding zones attempt to make up for the unit.

3.2.1.6 IMPROPER COOLING STAGING

Description: This formula determines if too many stages turn on in a relatively short amount of time.

Cause: Control logic is not tuned/setup properly.

Validation: The fault can be validated by looking at the client's BMS. Delay times between stages are present, but not always utilized. Additionally, sorting out the difference between stages and compressors creates complicated situations in which the unit can energize too many compressors within a short amount of time.

Impact

> *Energy* - Could potentially cause excess energy consumption as a kW spike may occur if more than one stage turns on simultaneously.
>
> *Comfort* - If too many stages turn on in a small time frame, the change in zone temperature may be uncomfortable. Additionally, if cycling occurs, the capacity may decrease.

How the fault is fixed: This fault can be fixed simply by making a change in the BMS.

New Takeaways from manual investigation: There is opportunity for the client to optimize their staging settings. Adjusting the settings may not only prevent potential energy waste and peak demand issues, but could also improve the comfort of the space as the unit's control of conditions would be gradual instead of sudden.

3.2.1.7 SETPOINT NOT MET – ZAT – OVER COOLING – OCCUPIED/UNOCCUPIED

Description: This fault occurs when a machine's sensors and/or control logic cause the machine to actively cool a ZAT below the cooling setpoint by more than a threshold temperature difference for greater than a threshold time.

Causes:

- Faulty setpoint control logic.
- Malfunctioning device.

Validation: In the past, overcooling faults in the application of this equipment were often falsely diagnosed as a result of dehumidification. Unfortunately, Ezenics is unable to pull a dehumidification command/status from this client to use as a criteria point to prevent false diagnosis. To handle these false positives, Ezenics has constructed a virtual dehumidification command that mirrors the equipment's logic, allowing for accurate fault detection. After adding the virtual criteria point to rule out these false positives, overcooling faults could be validated by examining the BMS control logic.

Impact

Energy – Impact is realized as unnecessary energy is spent cooling the unit beyond the setpoint.

Comfort – Controlling the space temperature below the setpoint can result in comfort issues.

How the fault is fixed:

- Correct the setpoint logic.
- Repair or replace malfunctioning component(s).

New Takeaways from manual investigation: To prevent food spoilage, these locations often control space conditions within certain zones and the overall store to a certain dewpoint setpoint. It was discovered that this fault was being caused on unit 24 at location 100 because the unit was using relative humidity to control dehumidification. The problem was the unit was actually significantly lower than the desired dewpoint of 53°F, but the unit continued to cool because the relative humidity setpoint was 51% with a hysteresis of 2%. The more the RTU overcooled sensibly, the higher the relative humidity rose, causing the unit to run unnecessarily. As you can see in Figure 3 below, the zone dewpoint and zone temperature never cross their corresponding setpoints, yet cooling is enabled for significant portions of each day. Cooling is only disabled when the cooling lockout is passed at night or the ZAT falls below its minimum threshold of 65°F. Usually heating is then turned on overnight to compensate for the overcooling. Correcting this problem is a significant energy saving opportunity.

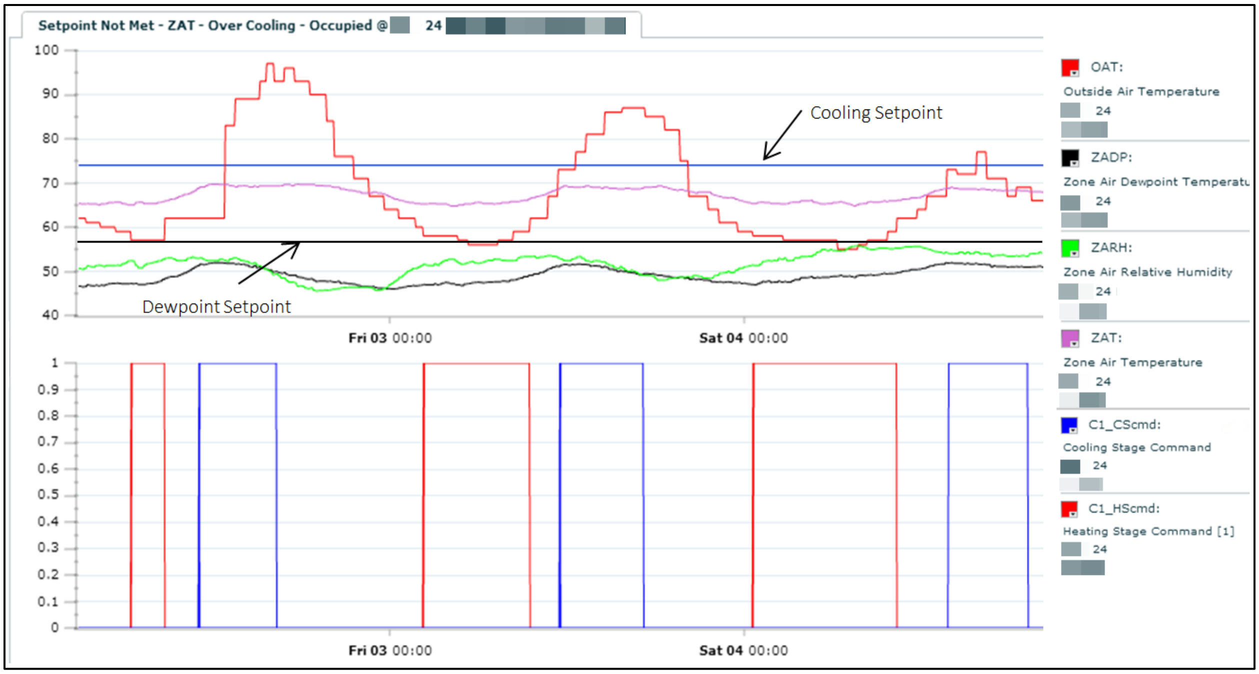

Figure 3 - Unit using RH for Dehumidification Control

3.2.1.8 ZAT DRIFT: COOLING/HEATING NOT ACTIVATED - OCCUPIED/UNOCCUPIED

Description: This formula determines if the ZAT is a threshold away from setpoint with the cooling or heating equipment off when the conditions are such that the cooling or heating equipment should be on.

Causes:

- Control logic is not tuned/setup properly.
- Controlling sensor has failed.
- Cooling or heating is locked out.

Validation: The fault can be validated by looking at the client's BMS.

Impact

> *Comfort* - If too many stages turn on in a small time frame, the change in zone temperature may be uncomfortable. Additionally, if cycling occurs, the capacity may decrease.

How the fault is fixed: This fault can be fixed simply by making a change in the BMS.

New Takeaways from manual investigation: Several different causes and contributing factors were found for this fault. Location 162 unit 19 experienced this fault at the beginning of the day. The machine would enter into an occupied mode, but would not activate cooling for about two hours even though the ZAT was regularly in the low to mid 80 degrees Fahrenheit range. The OAT was favorable for economizing, but the unit ran its cooling all day until entering an unoccupied mode. Had the unit utilized the free cooling, this fault would not have occurred and the zone would likely have been much cooler and closer to setpoint.

A second example at location 237 unit 4 occurred because of the lockout temperature setpoint. The OAT was again favorable for free cooling; had the free cooling been utilized, this fault would not have occurred. For a heating example at location 156, unit 19 had a ZAT sensor that went in and out of correct readings. This sensor fluctuates between negative values, values in the 10 to 50 degree range, and then values in the normal 70 degree range. As ZAT is a crucial input to this formula and to the operation of the machine, it is necessary to repair or replace that sensor so that the zone is adequately conditioned.

3.2.1.9 COMMAND VS STATUS MISMATCH - LIGHTS OFF

Description: This formula identifies when the lighting command and status point do not match, and the lighting is off.

Causes:

- Malfunctioning components.
- Manual control override(s).

Validation: The fault can be validated by looking at the client's BMS.

Impact

> *Comfort* - If the lights are not on when they should be, the location may not be lit properly.

How the fault is fixed: This fault can be fixed simply by checking any manual override equipment.

New Takeaways from manual investigation: Fixing the situation so this fault stops occurring is not as fast as adjusting a setpoint, but it is just as simple. Checking the override switching equipment is a relatively quick and easy fix, because specialized help is not needed.

3.2.1.10 COMMAND VS STATUS MISMATCH - LIGHTS ON; INCORRECT LIGHTING ACTIVATION

Description: This formula identifies when the lighting command and status point do not match, and the lighting is on. Additionally, situations where the lighting deactivation is delayed and the lighting reactivation occurs prematurely are diagnosed.

Causes:

- Malfunctioning components.
- Manual control override(s).

Validation: The fault can be validated by looking at the client's BMS.

Impact

Energy - If the lights are on when they should not be, energy is consumed unnecessarily.

How the fault is fixed: This fault can be fixed simply by checking any manual override equipment.

New Takeaways from manual investigation: Fixing the situation so this fault stops occurring is not as fast as adjusting a setpoint, but it is just as simple. Checking the override switching equipment is a relatively quick and easy fix, because specialized help is not needed.

3.2.1.11 HOA SWITCH: MANUAL MODE

Description: This formula identifies when the HOA switch is in the manual mode position for longer than a threshold amount of time.

Causes: manual control override(s).

Validation: The fault can be validated by looking at the client's BMS.

Impact

> *Comfort* - If the lights are not on when they should be, the location may not be lit properly.
>
> *Energy* - If the lights are on when they should not be, energy is consumed unnecessarily.

How the fault is fixed: This fault can be fixed simply by checking any manual override equipment.

New Takeaways from manual investigation: Fixing the situation so this fault stops occurring is not as fast as adjusting a setpoint, but it is just as simple. Checking the override switching equipment is a relatively quick and easy fix, because specialized help is not needed.

3.2.2 MECHANICAL FAULTS

Mechanical faults are usually caused by the breakdown or contamination of a physical component. An example of a mechanical component breakdown would be a fouled evaporator coil in a Rooftop Unit (RTU) causing a cooling stage failure. The effect of a mechanical failure can impact both customer comfort and building energy consumption. In the previous example, the cooling stage failure causes extended runtimes thus increasing energy costs. There could also be comfort impact as the RTU may have difficulty maintaining the zone's cooling setpoint. Table 6 below contains a summary of the mechanical faults for all locations.

Table 6 - Mechanical Faults Summary

Fault	System	# of Machines with Fault	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Return Air Temperature Sensor Failure: Unexpected Value	HVAC	12	$0.00	7	BMS Analysis/On-site validation	1	14%
Supply Air Temperature Sensor Failure: Unexpected Value	HVAC	23	$0.00	2	On-site Validation	1	50%
Zone Air Relative Humidity Sensor Failure: Unexpected Value	HVAC	19	$0.00	2	On-site Validation	2	100%
Zone Air Temperature Sensor Failure: Unexpected Value	HVAC	13	$0.00	4	On-site Validation	4	100%
Cooling Low Efficiency (Stage(s) #, #, #, #)– Steady State	HVAC	115	$0.00	57	On-site Validation	50	88%
Cooling Stage # Failure - Startup	HVAC	237	$0.00	69	On-site Validation	56	81%
Cooling Stage # Cycling	HVAC	378	$0.00	35	On-site Validation	29	83%
Heating Low Efficiency (Stage(s) #, #, #, #) - Steady State	HVAC	14	$0.00	5	On-site Validation	5	100%
Heating Stage # Failure - Startup	HVAC	33	$0.00	6	On-site Validation	5	83%
Heating Stage # Cycling	HVAC	176	$0.00	10	On-site Validation	10	100%

Fault	System	# of Machines with Fault	Impact ($)	Validation Attempted	Validation Method	# Validated	% Accuracy (# Validated / Validation Attempted)
Setpoint Not Met - ZAT - Under Cooling - Occupied/Unoccupied	HVAC	119	$0.00	56	On-site Validation	49	88%
Setpoint Not Met - ZAT - Under Heating - Occupied/Unoccupied	HVAC	21	$0.00	7	On-site Validation	7	100%
Supply Air Fan Cycling	HVAC	408	$0.00	16	On-site Validation	16	100%

Each mechanical fault from the table above is discussed in the following section. Each fault explanation contains the fault description, fault cause, how the fault was validated, the impact of said fault, and how the fault would be fixed. After the explanation of each fault, there is a 'takeaways' section that discusses new knowledge gained from the manual investigation of the fault.

3.2.2.1 RETURN AIR TEMPERATURE SENSOR FAILURE: UNEXPECTED VALUE

Description: This fault will be diagnosed if the sensor reading is less than a low limit or greater than a high limit.

Cause: The sensor is fine but is in a poor location, the sensor has failed, or there is a data problem.

Validation: The fault can be validated by looking at the client's BMS for extreme values (such as a -60.2, indicating the sensor failed) or by on-site validation.

Impact

> *Energy* – Depending on the control strategy in place, additional outside air could be brought in because the control logic thinks the outside air is cooler than the RAT. The equipment in this study usually does not employ this type of strategy, but has been seen with other equipment.
>
> *Comfort* – There is potential for too much heating or cooling to occur if the RAT is used for space control.

How the fault is fixed: The fault can be fixed simply by replacing the sensor, relocating the sensor, or fixing the data feed.

New Takeaways from manual investigation: Some thresholds need to be adjusted for this formula as a result of plenum return. If the unit is turned off for some reason on a hot day, the RAT sensor may start to read values similar to the OAT. If it is hot enough outside, the high end threshold may be exceeded causing a false fault to be diagnosed. A simple threshold adjustment will prevent the false positives that were detected, as indicated by Table 6.

3.2.2.2 SUPPLY AIR TEMPERATURE SENSOR FAILURE: UNEXPECTED VALUE

Description: This fault will be diagnosed if the sensor reading is less than a low limit or greater than a high limit.

Cause: The sensor is fine but is in a poor location, the sensor has failed, or there is a data problem.

Validation: The fault can be validated by looking at the client's BMS for extreme values (such as a -60.2, indicating the sensor failed) or by on-site validation.

Impact

> *Energy* – Some control strategies use an SAT setpoint to dictate the amount of cooling or heating that is required. A sensor that exceeds a high or low limit could cause excess runtimes. This equipment usually does not use an SAT setpoint to control zone conditions, but this strategy is often times employed by equipment.
>
> *Comfort* – Just as a bad supply air temperature sensor could cause excess runtimes, it could also cause short runtimes leading to a comfort issue. This equipment usually does not use an SAT setpoint to control zone conditions, but this strategy is often times employed by equipment.

How the fault is fixed: The fault can be fixed simply by replacing the sensor, relocating the sensor, or fixing the data feed.

New Takeaways from manual investigation: Ezenics was able to detect a unit that was blowing 150°F or higher heat into a zone that was dropping below the heating setpoint overnight as a result of refrigeration equipment within the zone. The extremely high SAT was doing very little to actually warm the zone, which was likely as a result of the stratification occurring.

3.2.2.3 ZONE AIR RELATIVE HUMIDITY SENSOR FAILURE: UNEXPECTED VALUE

Description: This fault will be diagnosed if the sensor reading is less than a low limit or greater than a high limit.

Cause: The sensor is fine but is in a poor location, the sensor has failed, or there is a data problem.

Validation: The fault can be validated by looking at the client's BMS for extreme values (such as a -60.2, indicating the sensor failed) or by on-site validation.

Impact

> *Energy* – Some control strategies use ZARH along with ZAT to determine a zone air dewpoint temperature (ZADP). If the ZARH is reading values too high, an RTU could be incorrectly led to enable cooling for dehumidification, which results in excess energy consumption.
>
> *Comfort* – If the ZARH reading is incorrect, the moisture levels in the space could be controlled improperly, resulting in uncomfortable conditions for occupants.

How the fault is fixed: The fault can be fixed simply by replacing the sensor, relocating the sensor, or fixing the data feed.

New Takeaways from manual investigation: It was found through on-site investigation that the ZARH sensor was placed directly above a refrigerated case. The sensor would then be exposed to cooling constantly, which can result in ZARH readings due to the dehumidifying properties of sensibly reducing the dry-bulb temperature of the air. In another situation, the ZARH sensor was found to be wired to a port on the refrigeration system. As a result, the values read by the HVAC system were constantly at 100%.

3.2.2.4 ZONE AIR TEMPERATURE SENSOR FAILURE: UNEXPECTED VALUE

Description: This fault will be diagnosed if the sensor reading is less than a low limit or greater than a high limit.

Cause: The sensor is fine but is in a poor location, the sensor has failed, or there is a data problem.

Validation: The fault can be validated by looking at the client's BMS for extreme values (such as -60.2 indicating the sensor failed) or by on-site validation.

Impact

> *Energy* – ZAT sensor failure has huge implications in terms of energy impact. Required cooling and heating could very easily have excess runtimes as a substitute is usually employed to dictate heating and cooling. For example, the equipment has two different strategies for ZAT failure: they either use the outdoor air temperature which is converted linearly to dictate how much heating/cooling is needed as seen in Figure 4, or they use the RAT sensor. Using the RAT sensor is usually an excellent strategy for ducted returns, but for plenum returns it is not optimal as the plenum conditions can be significantly different than the zone conditions.

Figure 4 - Outside Air Temperature Substitute for Zone Air Temperature

> *Comfort* – The cause of the comfort impact is the same as the energy impact stated above. Using a replacement sensor is not a good indicator of the actual conditions of the zone. Overcooling and undercooling can very easily occur.

How the fault is fixed: The fault can be fixed simply by replacing the sensor, relocating the sensor, or fixing the data feed.

New Takeaways from manual investigation: It was found through data analysis that supply fan cycling was being caused by a failing ZAT sensor flipping back and forth between a realistic temperature value and a default, failed value of -60.2°F. In another situation, on-site investigation resulted in discovering that the thermostat had not been replaced and the wires were simply dangling in the zone. This situation also led to failed ZAT values.

3.2.2.5 COOLING STAGE # FAILURE - STARTUP

Description: This formula diagnoses a stage failure in startup mode if the change in SAT is less than an expected threshold for cooling after a certain timespan.

Cause: There are a number of causes of a startup failure as listed below:

- Compressor breaks down.
- Dirty Coils (poor heat transfer).
- Poor sensor placement – this may cause a "false positive". A coil in good working condition may throw a fault if the SAT sensor is poorly located. On the other hand, a poorly located SAT sensor could prevent the detection of a cooling stage failure fault.
- Bad heating element – For example: a heating valve stuck partially open could raise the SAT, causing this fault to be detected.
- Low refrigerant.
- Low airflow.

Validation: On-site by KEC. Findings listed below:

- Broken supply fan belt.
- No or low refrigerant.
- Compressor issues:
  - Severed wiring.
  - Internal windings shortage.
  - Ceased or poor operation.
  - Incorrect BMS information on compressor count.
- Dirty air filter.
- Fouled cooling coil.
- Inoperable condenser fans.
- Failed contactors.
- High pressure switch wiring issues.

Impact

Energy – Failed stages will cause the compressor to run significantly longer to achieve the desired temperature change, or more compressors could be turned on to make-up for a failed stage.

Comfort – There is potential for undercooling and under-dehumidifying in the zone as the unit's cooling capacity is lowered.

How the fault is fixed:

- Replace/repair the compressor.
- Clean coil.
- Replace filter.
- Relocate SAT sensor.
- Replace or repair the heating element.
- Properly charge refrigerant.
- Inspect fan or ductwork for causes for loss in pressure.
- Replace supply fan belt.
- Repair condenser fans.

New Takeaways from manual investigation: Previous causes Ezenics had given for the fault were fairly general such as “Compressor breaks down”, but through the on-site validation by KEC more specific causes were able to be added to the fault causes. During early analysis prior to the on-site validation, a data handling issue causing a small number of data issues was discovered that was quickly corrected. This correction helped on the on-site verification to be extremely accurate as seen in Table 6.

3.2.2.6 COOLING LOW EFFICIENCY (STAGE(S) #, #, #, #) – STEADY STATE

Description: This formula detects a lower than expected SAT change after a cooling stage is on then diagnoses stage low efficiency in steady state mode (the # represents any combination of stages on at the same time, such as 1, 2 or 1, 2, 3, 4).

Cause: There are a number of causes of a cooling low efficiency as listed below:

- Compressor breaks down.
- Dirty Coils (poor heat transfer).
- Poor sensor placement – this may cause a "false positive". A coil in good working condition may throw a fault if the SAT sensor is poorly located. On the other hand, a poorly located SAT sensor could prevent the detection of a cooling stage failure fault.
- Bad heating element – For example: a heating valve stuck partially open could raise the SAT.
- Outside air damper leakage or stuck damper – If the unit is lacking a mixed air temperature (MAT) sensor, a virtual MAT is calculated to compare the temperature change across the cooling stages. A leaky damper would throw off the virtual MAT calculation causing an incorrect change in temperature result. This issue would still cause energy impact, but the cause of the inefficiency is not directly related to the cooling stage(s) itself.
- Low refrigerant as evidenced by refrigerant measurement and oil leakage.
- Low airflow.

Validation: On-site by KEC. Findings listed below:

- Broken supply fan belt.
- No or low refrigerant.
- Compressor issues:
  - Severed wiring.
  - Internal windings shortage.
  - Ceased or poorly operating.
- Dirty air filter.
- Fouled cooling coil.
- Inoperable condenser fans.
- Simultaneous heating and cooling.
- Reversed lockout temperature (acting as a heating lockout instead of cooling lockout).
- Failed contactors.

Impact

Energy – Low efficiency stages will cause the compressor to run significantly longer to achieve the desired temperature change, or more compressors could be turned on to make-up for an inefficient stage.

Comfort – There is potential for undercooling and under-dehumidifying in the zone as the unit's cooling capacity is lowered.

How the fault is fixed:

- Replace/repair the compressor.
- Clean coil.
- Replace filter.
- Relocate SAT sensor.
- Replace or repair the heating element.
- Properly charge refrigerant.
- Inspect fan or ductwork for causes for loss in pressure.
- Inspect dampers to ensure they are not stuck or leaking.
- Replace supply fan belt.
- Repair condenser fans.

New Takeaways from manual investigation: Previous causes Ezenics had given for the fault were fairly general such as "Compressor breaks down", but through the on-site validation by KEC more specific causes were able to be added to the fault causes.

3.2.2.7 COOLING STAGE # CYCLING

Description: This fault detects when the frequency of a cooling stage is cycling in its operation from on and off within a short amount of time.

Cause:

- Control issues – small deadband or minimum duration not in place.
- Equipment oversizing.
- Sensor location/failure.

Validation: The fault can be validated by checking the client's BMS to determine staging operation or by on-site validation. Findings by KEC are below:

- Sensor is close to supply diffusers in several situations.
- Sensor is close to food service sink, where hot water and steam can affect readings.

Impact

> *Comfort* – Comfort impact is dependent on the cause of the fault. For example: through data validation, we found that a ZAT sensor that was in the process of failing was causing the unit to cycle on and off. When the sensor was in its failed state, it would read -60.2, causing the unit to turn off. When it was reading a legitimate value, it was above the cooling setpoint causing the unit to turn on. Fluctuation in zone temperature could result from the equipment cycling, which can be uncomfortable for occupants.
>
> *Maintenance* – Most of the impact of cycling faults are as a result of the unnecessary change in device status causing early failure and component replacement.

How the fault is fixed:

- Fix control logic by setting up minimum duration times or increasing the deadband.
- Replace or relocate sensor.

3.2.2.8 HEATING STAGE # FAILURE - STARTUP

Description: This formula diagnoses a stage failure in startup mode if the change in SAT is less than an expected threshold for heating after a certain timespan.

Cause: There are a number of causes of a startup failure as listed below:

- Compressor breaks down (applicable to heat pumps only).
- Dirty coils/heating element (poor heat transfer).
- Poor sensor placement – this may cause a "false positive". A coil in good working condition may throw a fault if the SAT sensor is poorly located. On the other hand, a poorly located SAT sensor could prevent the detection of a heating stage failure fault.
- Bad heating element – For example: a heating valve stuck partially open instead of full open could prevent the SAT from rising to complete capacity. An electric resistance heater could be failing.
- Low refrigerant (heat pump only).
- Low airflow.

Validation: On-site by KEC. Findings listed below:
- Induced draft fan motor is going bad. Motor was receiving voltage but was not running.
- Unit does not provide any heat.
- Dirty filter and heating coil.

Impact

Energy – Failed stages will cause the heating stages to run significantly longer to achieve the desired temperature change, or additional heating stages could be turned on to make-up for a failed stage.

Comfort – There is potential for under-heating in the zone as the unit's heating capacity is lowered.

How the fault is fixed:

- Replace/repair the compressor (heat pumps only).
- Clean coils/heating element.
- Relocate SAT sensor.
- Replace or repair the heating element.
- Properly charge refrigerant (heat pump only).
- Inspect fan or ductwork for causes of loss in pressure.

New Takeaways from manual investigation: Through KEC's onsite validation, a new airflow fault cause was able to be added to Ezenics' database of fault causes.

3.2.2.9 HEATING LOW EFFICIENCY (STAGE(S) #, #, #, #) – STEADY STATE

Description: This formula detects a lower than expected SAT change after a heating stage is on then diagnoses stage low efficiency in steady state mode (the # represents any combination of stages on at the same time, such as 1, 2 or 1, 2, 3, 4).

Cause: There are a number of causes of a heating low efficiency as listed below:

- Compressor breaks down (applicable to heat pumps only).
- Dirty coils/heating element (poor heat transfer).
- Poor sensor placement – this may cause a “false positive”. A coil in good working condition may throw a fault if the SAT sensor is poorly located. On the other hand, a poorly located SAT sensor could prevent the detection of a heating stage failure fault.
- Bad heating element – For example: a heating valve stuck partially open instead of full open could prevent the SAT from rising to complete capacity. An electric resistance heater could be failing.
- Outside air damper leakage or stuck damper – If the unit is lacking a mixed air temperature (MAT) sensor, a virtual MAT is calculated to compare the temperature change across the cooling stages. A leaky damper would throw off the virtual MAT calculation causing an incorrect change in temperature as a result. This issue would still cause energy impact, but the cause of the inefficiency is not directly related to the heating stage itself (or heating stages themselves).
- Low refrigerant (heat pump only).
- Low airflow.

Validation: On-site by KEC. Findings listed below:

- Induced draft fan motor is going bad. Motor was receiving voltage but was not running.
- Unit does not provide any heat.
- Dirty filter and heating coil.
- Circuit board is disabled.

Impact

Energy – Low efficiency stages will cause the heating stages to run significantly longer to achieve the desired temperature change, or more heating stages could be turned on to make-up for an inefficient stage.

Comfort – There is potential for underheating in the zone as the unit’s heating capacity is lowered.

How the fault is fixed:

- Replace/repair the compressor (heat pumps only).
- Clean coils/heating element.
- Relocate SAT sensor.
- Replace or repair the heating element.
- Inspect the outside air damper to see if the damper is stuck or leakage is occurring.
- Properly charge refrigerant (heat pump only).
- Inspect fan or ductwork for causes of loss in pressure.

New Takeaways from manual investigation: Through KEC's onsite validation, a new airflow fault cause was able to be added to Ezenics' database of fault causes.

3.2.2.10 HEATING STAGE # CYCLING

Description: This fault detects when the frequency of a heating stage is cycling in its operation from on and off within a short amount of time.

Cause:

- Control issues – small deadband or minimum duration not in place.
- Equipment oversizing.
- Sensor location/failure.

Validation: The fault can be validated by checking the client's BMS to determine staging operation or by on-site validation. Findings by KEC are below:

- Sensor is close to supply diffusers in several situations.
- Sensor is close to refrigeration freezers/coolers.

Impact

> *Comfort* – Comfort impact is dependent on the cause of the fault. For example: through data validation, we found that a ZAT sensor that was in the process of failing was causing the unit to cycle on and off. When the sensor was in its failed state, it would read -60.2, causing the unit to turn off. When it was reading a legitimate value, it was above the cooling setpoint causing the unit to turn on. Fluctuation in zone temperature could result from the equipment cycling, which can be uncomfortable for occupants.
>
> *Maintenance* – Most of the impact of cycling faults are as a result of the unnecessary change in device status causing early failure and component replacement.

How the fault is fixed:

- Fix control logic by setting up minimum duration times or increasing the deadband.
- Replace or relocate sensor.

3.2.2.11 OAT/OARH/OAE MISMATCH

Description: If the outside air temperature, relative humidity, or enthalpy from the machine and the local weather station are more than a threshold value different from each other for greater than a threshold time, a fault is diagnosed.

Causes:

- Sensor out of calibration
- Improper sensor placement

Validation: On-site by KEC. Findings listed below

- Sensors out of calibration.
- It appears that during certain times of the day the temperature reading significantly spikes, indicating it is in direct sunlight. KEC was unable to confirm this hypothesis as they were unable to find the sensor on the building.

Impact

Energy – Economizer dampers may not be working properly.

Comfort – In extreme mismatch cases, units in economizing mode could allow in air greatly affecting the zone conditions and causing comfort problems. This problem especially applies to issues with OARH sensors out of calibration for grocery applications.

How the fault is fixed:

- Repair or replace sensor.
- Relocate sensor.

New Takeaways from manual investigation: None

3.2.2.12 SETPOINT NOT MET – ZAT – UNDER COOLING – OCCUPIED/UNOCCUPIED

Description: This fault occurs when a machine's sensors and/or control logic cause the machine to actively cool a ZAT above the cooling setpoint by more than a threshold temperature difference for greater than a threshold time.

Causes:

- Faulty setpoint control logic.
- Inadequate unit capacity.
- Malfunctioning device.

Validation: This fault is generally systemic and usually correlates to another fault that is occurring. These faults were deemed validated if faults such as a cooling stage failure or inefficiency were also found as the resulting unit cooling capacity was significantly lowered.

Impact

> *Energy* – If the fault is caused by a mechanical failure, the unit would have extended runtimes as it tries to meet the effective cooling setpoint.
>
> *Comfort* – A unit unable to meet setpoint or controlled above the setpoint can result in comfort issues.

How the fault is fixed:

- Correct setpoint logic.
- Investigate unit as to potential issues affecting unit capacity.
- Repair or replace malfunctioning component(s).
- Remedy problematic sensor location.

New Takeaways from manual investigation: While this fault is often a systemic fault that occurs as a result of a mechanical component failing, other interesting issues were found related to sensor placement. Two instances were found where the ZAT sensor location was causing the problem. At location 140, a wall was built through a section of the stockroom. The majority of the supply diffusers were on one side of the wall and the ZAT sensor was on the other side. In this scenario, the unit may have been providing enough cooling capacity to meet the setpoint, but the division prevented the ZAT sensor from immediately feeling the effects of the cooling. At location 173, unit 15, the RTU supplies cooling and heating to the shoes portion of the sales floor, but the thermostat was located in the electronic stock room. The stockroom space conditions are being controlled by a different RTU with much less stringent setpoints. Because of this situation, the actual sales floor may be severely overcooled because the thermostat is unaffected by the cooling the RTU supplies.

3.2.2.13 SETPOINT NOT MET – ZAT – UNDER HEATING – OCCUPIED/UNOCCUPIED

Description: This fault occurs when a machine's sensors and/or control logic cause the machine to actively heat a ZAT below the heating setpoint by more than a threshold temperature difference for greater than a threshold time.

Causes:

- Faulty setpoint control logic.
- Inadequate unit capacity.
- Malfunctioning device.

Validation: This fault is generally systemic and usually correlates to another fault that was occurring. These faults were deemed validated if faults such as a heating stage failure or inefficiency were also found as the resulting unit heating capacity was significantly lowered.

Impact

> *Energy* – If the fault is caused by a mechanical failure, the unit would have extended runtimes as it tries to meet the effective heating setpoint.
>
> *Comfort* – A unit unable to meet setpoint or controlled below the setpoint can result in comfort issues.

How the fault is fixed:

- Correct setpoint logic.
- Investigate unit as to potential issues affecting unit capacity.
- Repair or replace malfunctioning component(s).
- Remedy problematic sensor location.

New Takeaways from manual investigation: While this fault is often a systemic fault that occurs as a result of a mechanical component failing, other interesting issues were found related to sensor placement. Two instances were found where the ZAT sensor location was causing the problem. At location 140, a wall was built through a section of the stockroom. The majority of the supply diffusers were on one side of the wall and the ZAT sensor was on the other side. In this scenario, the unit may have been providing enough heating capacity to meet the setpoint, but the division prevented the ZAT sensor from immediately feeling the effects of the heating. At location 173, unit 15, the RTU supplies cooling and heating to the shoes portion of the sales floor, but the thermostat was located in the electronic stock room. The stockroom space conditions are being controlled by a different RTU with much less stringent setpoints. Because of this situation, the actual sales floor may be severely overheated because the thermostat is unaffected by the cooling the RTU supplies.

3.2.2.14 SUPPLY AIR FAN CYCLING

Description: This fault detects when the frequency of the supply fan is cycling in its operation from on and off within a short amount of time.

Cause:

- Control issues – small deadband or minimum duration not in place.
- Equipment oversizing.
- Sensor location/failure.

Validation: The fault can be validated by checking the client's BMS to determine fan operation or by on-site validation. Findings by KEC are below:

- Environmental conditions (ZAT sensor too close to supply diffuser).
- Bad physical contacts.
- Fan motor shaft bent, causing increased power draw then thermal overload switch trip.

Impact

> *Comfort* – Comfort impact is dependent on the cause of the fault. For example: through data validation, we found that a ZAT sensor that was in the process of failing was causing the unit to cycle on and off. When the sensor was in its failed state, it would read -60.2, causing the unit to turn off. When it was reading a legitimate value, it was above the cooling setpoint causing the unit to turn on.
>
> *Maintenance* – Most of the impact of cycling faults are as a result of the unnecessary change in device status causing early failure and component replacement.

How the fault is fixed:

- Fix control logic by setting up minimum duration times or increase the deadband.
- Replace or relocate sensor.

3.2.3 ADDITIONAL FINDINGS

During the on-site validation efforts, Ezenics also had KEC investigate machines that the Ezenics platform was not generating faults for. The purpose of this exercise is to ensure any issues that are occurring on the machine but that are not being diagnosed by the AFDDI platform are caught by the platform in the future. The necessary changes or additions to formulas would be made to increase the breadth and dependability of the formula library.

Table 7 - No Faults Summary

Fault	*System*	*# of Machines with Fault*	*Impact ($)*	*Validation Attempted*	*Validation Method*	*# Validated*	*% Accuracy (# Validated / Validation Attempted)*
No Faults	HVAC	7	0	7	On-site Validation	7	100.00%

From Table 7, it is apparent that Ezenics has a robust set of algorithms for use on the RTUs. The fact that no issues were found on the machines is further validation of the accuracy of the formulas.

4. CONCLUSION

While sensors are not perfect in terms of their nominal sensor value, they can still be used to identify problems with a high level of accuracy and precision as shown in the on-site validation results. Results also revealed that there is a huge opportunity in identifying and repairing control issues that result in both comfort and energy problems with a quick return on investment. Mechanical failures, which are more difficult to detect and costly to repair, were also identified with a high level of success proving the validity and effectiveness of using AFDDI to decrease energy demand and consumption. The takeaways from this field study provide for changes to be made to improve the accuracy of formulas as the project advances to the 250 location setup phase.