Scaling Retro-Commissioning to Small Commercial Buildings: A Turnkey Automated Hardware-Software Solution

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ABSTRACT

In the United States, small commercial buildings represent 51% of total floor space of all commercial buildings and consume nearly 3 quadrillion Btu (3.2 quintillion joule) of site energy annually, presenting an enormous opportunity for energy savings. Retro-commissioning (RCx), the process through which professional energy service providers identify and correct operational problems, has proven to be a cost-effective means to achieve median energy savings of 16%. However, retro-commissioning is not typically conducted at scale throughout the commercial stock. Very few small commercial buildings are retro-commissioned because utility expenses are relatively modest, margins are tighter, and capital for improvements is limited. In addition, small buildings do not have in-house staff with the expertise to identify improvement opportunities. In response, a turnkey hardware-software solution was developed to enable cost-effective, monitoring-based RCx of small commercial buildings. This highly tailored solution enables non-commissioning providers to identify energy and comfort problems, as well as associated cost impacts and remedies. It also facilitates scale by offering energy service providers the means to streamline their existing processes and reduce costs by more than half. The turnkey RCx sensor suitcase consists of two primary components: a suitcase of sensors for short-term building data collection that guides users through the process of deploying and retrieving their data and a software application that automates analysis of sensor data, identifies problems and generates recommendations. This paper presents the design and testing of prototype models, including descriptions of the hardware design, analysis algorithms, performance testing, and plans for dissemination.

INTRODUCTION

In most commercial buildings, over 10% of site energy use can be saved by adjustments to incorrect operational schedules, suboptimal setpoints, and control problems (Mills, 2011). Retro-commissioning (RCx) is the process through which professional energy service providers identify and correct these problems, to improve efficiency and comfort. In large commercial buildings, RCx saves an average of 16% in whole-building energy use, with an average payback of just over one year (Mills, 2011). In small commercial buildings, the saving opportunities are similar, but the energy expenditures are much smaller. The average annual utility cost for buildings with floor areas of less than 50,000 ft^2 (4,645 m^2) is just $11,000, which tightly constrains the business economics of RCx and compromises cost effectiveness. In addition, small buildings do not typically have in-house staff with the sufficient building expertise to identify energy improvement opportunities. The result is that RCx is not typically conducted in small buildings, and payback and significant energy savings are lost. Even though the energy expenditures for this sector are small on a per-building basis, they represents a tremendous opportunity for overall energy savings due to the total size of the sector–by area, a full 50% of the U.S. commercial building stock is smaller than 50,000 ft^2 (4,645 m^2) (EIA, 2006).

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The current approach to existing building RCx involves a multi-step formal process led by an commissioning agent, in which an initial walk-through is performed, diagnostic monitoring and functional tests are conducted (often with temporary sensors or data loggers), field findings are documented and prioritized, and selected changes are implemented. In spite of the benefits, less than 1% of existing buildings are retro-commissioned for energy, even in California (Mills, 2011; PECI, 2000), which tends to lead the United States in energy-efficiency practices.

The current implementation rates, energy-saving opportunities, and cost-effectiveness challenges all indicate that a solution to enable scaled small building RCx would bring enormous value. Thus, we have developed a turnkey hardware-software solution (the RCx sensor suitcase). By (a) automating and simplifying the RCx process for the less complex systems used in small buildings and (b) enabling savings opportunities to be identified and prioritized by non-experts as well as professionals, the RCx sensor suitcase would enable the performance of the very large number of small commercial buildings to be improved cost effectively. This paper presents the design and testing of the prototype system, including descriptions of the hardware, analysis algorithms, analysis software, performance testing, and plans for dissemination.

TECHNOLOGY DESCRIPTION

The RCx sensor suitcase provides a turnkey hardware-software solution that offers a degree of simplicity and automation that will enable realization of RCx at scale in small commercial buildings. It consists of five primary components delivered as a single integrated solution:

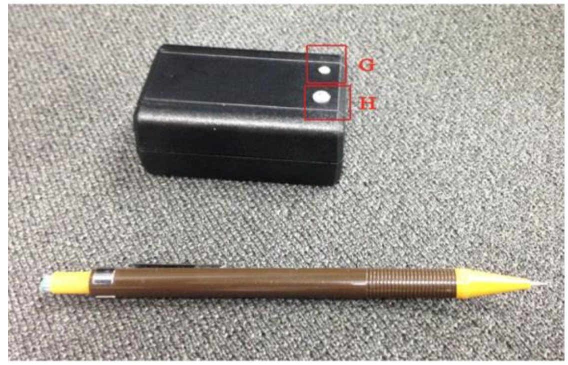
1. Easy-install battery-powered sensors (air temperature, light, and rooftop unit operating status) with on-board data storage.
2. A suitcase provides a means of transport, storage, charging capability and data transfer to a computer for analysis of the data collected.
3. A tablet to configure sensors, document information of sensors installed, and provides installation guidance.
4. Diagnostic algorithms to generate recommendations to improve building operations, utility costs, and energy performance. The algorithms target high-impact problems in lighting and HVAC system operations.
5. A software application with graphical user interface, which automatically analyzes data and outputs building-specific improvement recommendations to the user, along with cost impacts.

The five-step application process of the sensor suitcase is briefly described here. Step 1: Use the application in the tablet to individually configure each sensor and install it in the building. Step 2: Recover sensors from the building about 4–6 weeks after installation. Step 3: Return the sensors to the suitcase and use the tablet to initiate download of the sensor data to the suitcase. Step 4: Transfer the .csv sensor data files to a computer on which the analysis software is installed so the data can be used as inputs to the analysis software. Step 5: Run the software, and enter the building's utility bill information and occupancy schedule. The software then provides low-cost improvement recommendations and estimated utility costs savings from implementing the recommendations. The following subsections describe the five components of the solution in detail, categorized by hardware and software.

Hardware Package

The hardware system consists of three primary components, the suitcase itself, which provides slots for inserting sensors, a set of sensors/loggers, and a tablet computer. The current prototype of the suitcase (see Figure 1a) has slots (or ports) for 16 sensors. Each slot provides electrical connections that align with corresponding connectors on the sensors and is compatible with any of the sensors. The slots are wired to a single-board computer inside the suitcase that serves as a data control module. This control module runs firmware that configures each sensor during installation, downloads data from sensors after their retrieval at the end of the data collection period, stores the sensor data following download from the sensors until it is transferred to the computer on which the analysis software runs, and communicates wirelessly via Bluetooth with the tablet. The suitcase is powered by a rechargeable battery.

a)



b)

Figure 1. Photos of (a) an open sensor suitcase with 10 sensors inserted in slots and 6 empty slots with the electrical contacts for the sensors showing on the rear wall near the bottom of the most forward two empty slots and (b) a sensor with the LED (G) and window for the light sensor (H) highlighted.

Two basic types of sensors are provided. The first is configurable to measure either air temperature or the on/off status of electric lights. When configured for air-temperature measurements, the sensors are used to measure indoor ambient air temperature, the temperature of the air discharged from diffusers (diffuser air temperature), and the outdoor air temperature. When a sensor is configured to sense the status of electric lights, it is installed a few inches from the lamp directly facing it. The second type of sensor measures the operating status of rooftop packaged air conditioners and heat pumps—off, supply fan only on, or fully on (compressors, condenser fans, and supply fan all on)—using a vibration sensor and onboard processing. Both types of sensors are packaged identically, but the packaged unit status sensors are labelled as “HVAC” or “RTU” to help the installer ensure that a sufficient number of these sensors are brought to the site. Each sensor is powered by two replaceable ((non-rechargeable) AAA alkaline batteries. Diffuser air temperature and packaged unit status sensors measure conditions at one-minute intervals. The indoor and outdoor air temperature and the lighting status sensors record conditions once every five minutes.

Each sensor is configured and relevant information about its installation location and property measured is stored on the sensor during its configuration immediately prior to placement. Software on the tablet computer guides the user through the configuration/installation process for each sensor. The users enter information about the site, including, building name, address, time zone, and estimated floor area of the building. The user then goes to a room with a thermostat and begins the process of installing sensors. Generally, an indoor air temperature sensor, a diffuser air temperature sensor, and a lighting status sensor are installed in each room having a thermostat. The tablet guides the user through the process of configuring each sensor, one at a time. The user selects one of the sensor types to configure by clicking on the corresponding icon on the tablet display and then enters the room number or name into a field displayed on the tablet (or selected from a drop-down list, if a sensor was previously installed in the room). The user can read guidance for placement of the sensor and then clicks on an “Activate” button. The suitcase control module selects an appropriate sensor in the suitcase, configures it for the proper measurement and sampling interval, and stores information about the site and room on the sensor. The selected sensor then flashes a green LED, which notifies the user that this specific sensor is the one to install for this purpose and location specified. The LED continues flashing for 2 minutes so if the installer is briefly distracted the correct sensor can be identified. The user removes the flashing sensor from the suitcase and installs the sensor at the recommended location (e.g., on the wall next to the thermostat for the room air temperature sensor) using one of the mechanisms provided for mounting sensors (e.g., a command picture hanger). An example, sensor installation/configuration screen is shown in Figure 2.

The process is then repeated for the remaining sensors for the room. This process is repeated for all other rooms having a thermostat, for the outdoor temperature sensor, and for a status sensor for each packaged rooftop unit. Sensors are left in place for a recommended monitoring period of 4 to 6 weeks.

At the end of the monitoring period, the user returns to the site and retrieves all of the sensors. Upon retrieval, each sensor is inserted into an open sensor slot in the suitcase. The tablet guides the user in initiating download of the data to the suitcase control module. The downloaded data can then transferred from the suitcase to the analysis computer in a convenient time using an Ethernet cable connection between the suitcase and the computer.

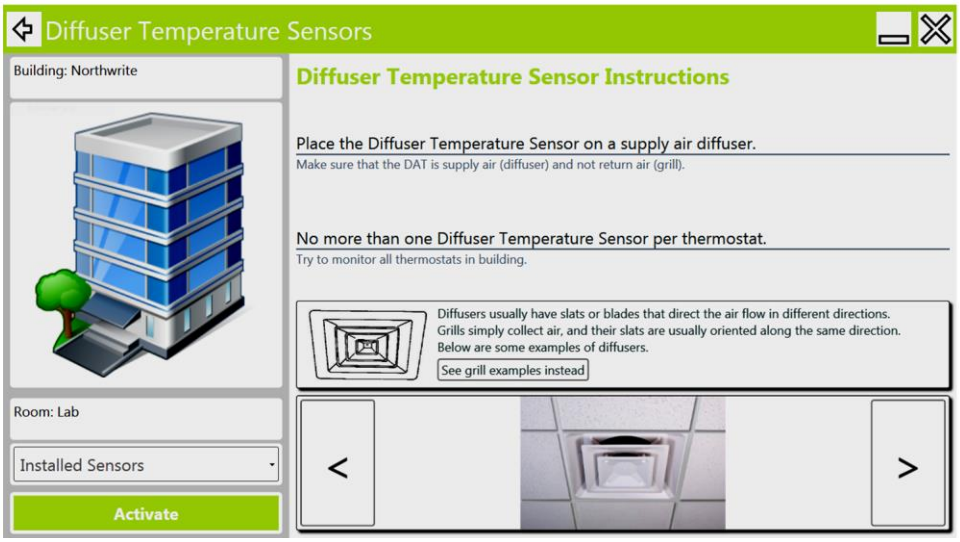


Figure 2. A sensor configuration screen from the tablet computer enabling configuration of a diffuser air temperature sensor.

Software Solution

Rule-based fault detection and diagnostic approaches have proved successful in building operational applications, and have been integrated into a number of tools. For example, the air handling unit performance assessment rules (APAR) for air handler diagnostics that were published by NIST (Schein, 2006) have been adapted for use in commercial analytical offerings. However, in contrast to the RCx sensor suitcase, these commercial offerings are typically targeted for large buildings, commonly with sophisticated building automation systems. In the RCx sensor suitcase solution, rule-based diagnostic algorithms are developed and embedded in the analysis software to identify savings opportunities and generate recommendations for eight common, high-impact problems in the control and operation of lighting and HVAC systems in small commercial buildings. The issues to be addressed are listed below.

1. Thermostat setbacks not enabled for unoccupied hours

Logic to detect: ASHRAE Standard 90.1 (2007) suggests that during unoccupied hours, the HVAC system shall have the capability to maintain indoor temperature above a heating setpoint adjustable down to 55°F (12.8°C) or lower, and below a cooling setpoint adjustable up to 90°F (32.2°C) or higher. Based on this suggestion, we conservatively assume that the building should be cooled to 80°F (26.7°C) or higher, or be heated to 60°F (15.6°C) or lower in the unoccupied time period. To identify this problem, for each thermostat that is monitored for diffuser and indoor air temperature, count the percentage of unoccupied hours for which the area is being heated, cooled, or purely ventilated when indoor air temperature is within the range of 60°F–80°F (15.6°C–26.7°C). The room conditioning status in all the algorithms is derived from rooftop unit (RTU) status and differences between diffuser and indoor air temperature according to expression (1). If heating, cooling, and ventilation occurs for more than 30% of the unoccupied hours in the monitoring period, the room/area is determined to have lack of thermostat setbacks.

$$\text{Room conditioning status} = \begin{cases} \text{Cooling } (if\ HS = 2\ and\ DAT < 0.9RAT) \\ \text{Heating } (if\ HS \neq 0\ and\ DAT > 1.1RAT) \\ \text{Ventilation } (if\ HS = 1) \end{cases} \quad (1)$$

Where

HS is rooftop unit status, 0=off, 1= supply fan only on, 2= fully on (compressors and fans all on)

DAT is diffuser air temperature in degree F, i.e., the temperature of the air discharged from diffusers

RAT is room indoor air temperature in degree F, usually measured near the thermostat

2. Over-cooling or over-heating during occupied hours (i.e., thermostat setpoints are too low for cooling and/or too high for heating)

Logic to detect: Based on a reasonable subset of ASHRAE Standard 55 (2004) maximum comfort ranges, we conservatively assume that the building should be cooled to 75°F (23.9°C) or higher, and be heated to 72°F (22.2°C) or lower, in the occupied time period. To identify this fault, for each thermostat that is monitored for diffuser and indoor air temperature, count the percentage or fraction of time for which the average indoor temperature is either cooled to less than 75°F (23.9°C) or heated to over 72°F (22.2°C), during occupied building hours. If this fraction of time is greater than 30% of the total occupied time in the monitoring period, over-cooling or over-heating is detected.

3. Heating and cooling setpoints too close together (i.e., there is an overly narrow thermostat dead band)

Logic to detect: For each thermostat, find the average temperature when the area is being actively heated or cooled during occupied hours. These average indoor temperatures are taken to be the heating and cooling setpoints. Compare the heating and cooling setpoints to a subset of the ASHRAE comfort zone (72°F, 75°F) (22.2°C, 23.9°C), representing minimum typical dead band-3°F (1.8°C). If the sensed heating setpoint is higher than 72°F (22.2°C) and the sensed cooling setpoint is lower than 75°F (23.9°C), an overly narrow dead band is identified, and both setpoints should be changed to widen the setpoint dead band.

4. Under-conditioning during occupied hours (i.e., thermostat setpoints are too low for heating or too high for cooling)

Logic to detect: For each thermostat that is monitored for diffuser and indoor air temperature, count the percentage for which the average indoor temperature is not cooled to less than 80°F (26.7°C) or not heated to more than 69°F (20.6°C) during the occupied building hours. If this percentage is greater than 30%, under-heating or under-cooling has been detected. This logic relies on the ASHRAE Standard 55 (2004) maximum acceptable comfort ranges of approximately 69°F–80°F (20.6°C–26.7°C) for humidity ranges commonly encountered in buildings (40% to 70%).

5. RTU short-cycling, with excess compressor on/off operation

Logic to detect: Rooftop unit compressor short cycling means that the compressor is enabled again shortly after being stopped for only a brief period of time (CUSCST, 2011). For each RTU status sensor, a short-cycling fault is identified if there are 10 or more consecutive cycles where the cycling time is less than five minutes (New Buildings Institute, 2011). The cycling time is determined by the time differences between two compressor starts.

6. Under-air side economizing (i.e., not making use of "free cooling")

Logic to detect: For each RTU status sensor and associated diffuser air temperature sensor, first determine when the unit could be economizing, i.e., the instances in which the RTU is either in supply fan only on mode or fully on mode, the outside air temperature is less than 65°F (18.3°C), and the area is being cooled (see expression(1)). Next determine also when the unit actually is economizing, i.e., the instance in which the RTU is in supply fan only on mode and the area is being cooled. If the unit is actually economizing less than 70% of the time that it could be economizing, under-use of free cooling has been detected.

7. Excessive lighting during occupied hours

Logic to detect: For each light sensor installed, during occupied hours, count the number of times per day that the light changes from on to off, and determine the time length per day when the light is on. Consider a day a fault flag day if on that day the room's sensors show that the light is not turned off more than two times per sensor per day, and the light is on for more than half of the occupied hours per sensor per day. If the number of fault flag days is more than half of the monitoring days, the room is determined to have excessive lighting during occupied hours.

8. Excessive lighting during unoccupied hours

Logic to detect: For each light sensor in the building, count the average time the lights are on during the building's unoccupied hours. If the average time on is greater than three hours per sensor per day (allowing for cleaning, security, and abnormal occupancy), the room is determined to have excessive lighting during unoccupied hours.

Associated energy cost impacts are estimated for each fault, from estimated energy savings and user-defined annual utility expense. The savings of thermostat-setpoint-related faults (1–4) are calculated following the rule of thumb that energy savings equal 1% of heating or cooling energy uses, per °F (per 0.6°C) of thermostat setpoint change, for each eight hours of setpoint change (U.S. DOE, 2014). Regarding compressor short-cycling, we conservatively estimate that 10% HVAC savings can be achieved by eliminating short-cycling, since literature suggests 15% increases in RTU electric consumption energy can occur in a severely short-cycling RTU (Pang, X. and Liu, M. 2011). Anecdotally, eliminating under-economizing is estimated to save approximately 10% savings in total HVAC energy use. The savings from elimating excessive lighting faults (7 and 8) are roughly estimated as 6% reduction of lighting load in occupied hours and 4% reduction in unoccupied hours (Von Neida, B et al. 2000).

All the diagnostic algorithms are coded with MATLAB and packaged to an executable file that can be called by the analysis software. The analysis software application with a graphical user interface was built to easily capture the building occupancy schedule and annual utility billing information from the user; collect, process, and analyze sensor data; and display recommendations and fault/energy findings. The software displays the outputs from the analysis algorithms in table/cell format, including problems identified, explanations as to why a problem was flagged (which pops-up when a user double-clicks the table), recommended ways to fix the problem, location of the problem, and estimated energy cost savings impacts. Figure 3 shows an example software output report.

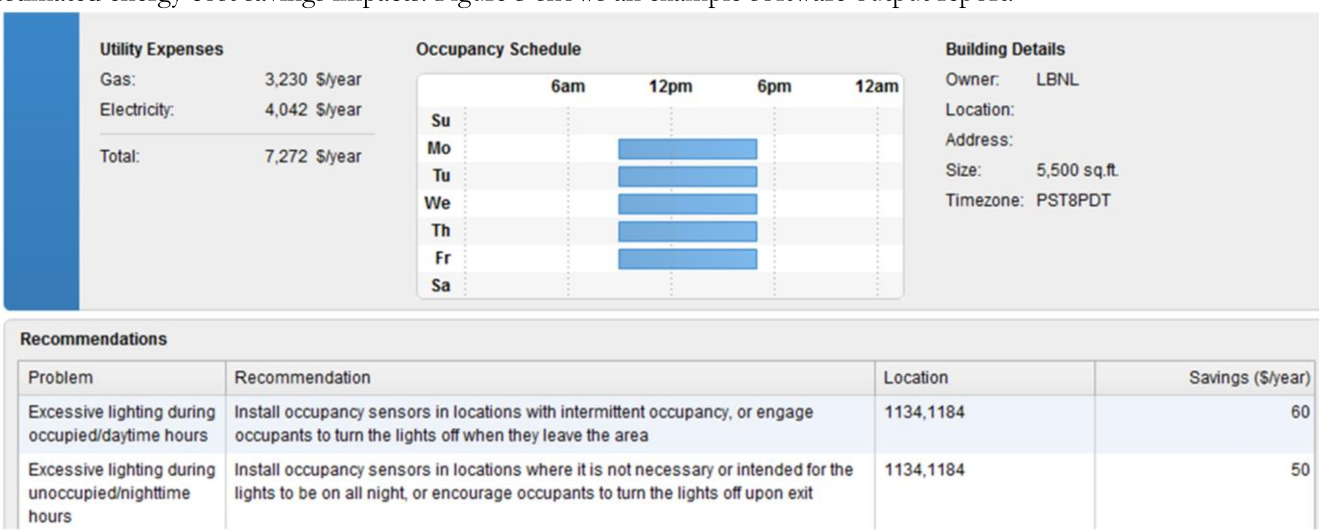
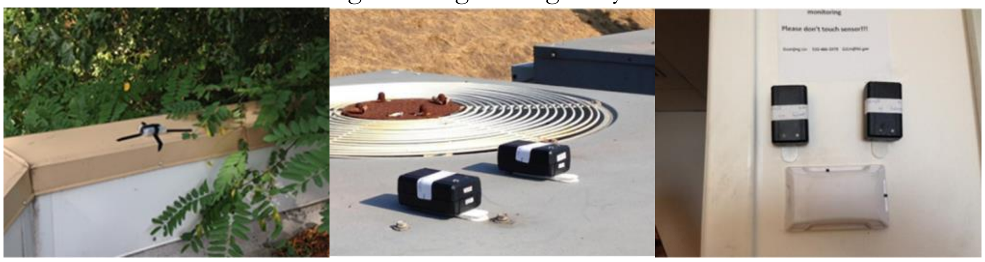


Figure 3. A screenshot from the analysis software output, identifying two problems in this example case.

FIELD TEST CASES

In this section, we validate the performance of the RCx sensor suitcase using actual field implementations, Site A—a small office building in Berkeley, California, and Site B—a mixed office/warehouse building in Lake Oswego, Oregon. The floor area of Site A and Site B are 5,500 ft^2 (511 m^2) and 10,000 ft^2 (9,290 m^2), respectively, and both sites are served by packaged rooftop units with gas heat. The field tests were individually performed by two energy service provider partners. These partners conducted the demonstration tests following the same procedure. They activated and configured the sensors individually with the tablet and installed the sensors in the buildings. Rooftop unit status sensors were placed on the top of each RTU, diffuser air temperature and indoor air temperature sensors were installed in the associated rooms with thermostats, outside air temperature sensors were placed on north side of the building, and lighting status sensors were installed in the conference rooms, private offices, and hallways. Figure 4 shows some photos of sensor installation. The sensors acquired data in the buildings for about a three-week period, and then the testers downloaded the data from the sensors and ran the analysis software. Feedback was provided by the testers on the usability, functionality, and performance of the hardware and software. In addition, the software recommendations were validated with trend logs and engineering analysis of the raw data.

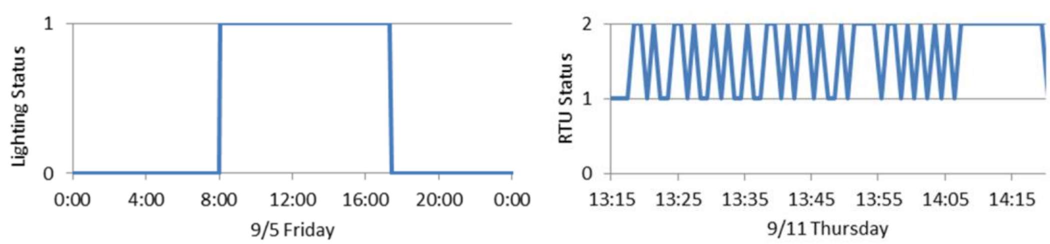


a) b) c)

Figure 4. Photos of (a) an outdoor air temperature sensor placed on the north side of the roof, (b) two rooftop unit sensors mounted on top of an RTU, and (c) two indoor air temperature sensors placed near a thermostat.

Test Findings

Testers of the sensor suitcase were surveyed regarding their experiences and perceptions in using the hardware. Key observations of the testers were: 1) the hardware provided sufficient data for the analysis software, 2) the suitcase guided sensor configuration and installation and can significantly reduce the labor time and required expertise, 3) the technology is versatile and provides data on actual operating conditions that wouldn't otherwise be available, and 4) the system complements existing products and services. Testers also provided suggestions for enhancements, which reinforced needs already identified by the development team, including weatherproofing of the outdoor sensors is needed, solar heating of the outdoor temperature sensors is necessary, and a diversity of mounting mechanisms is needed.



a) b)

Figure 5. Trends from sensors: (a) Site B, trend from a lighting status sensor (1=lighting on, 0=lighting off) on a weekday during the monitoring period, (b) Site B, example trend from a rooftop unit status sensor (0=off, 1= supply fan only on, and 2= compressors, condenser fans, and supply fan all on) during the monitoring period

The testers installed the analysis software and ran it with the gathered sensor data. They thought the software was generally easy to use, and the generated results were reasonable. Three problems were noted in Site A, including over-cooling for occupied hours and excessive lighting during occupied and unoccupied hours. Three percent of Site A's annual utility expense could be saved if all the problems are fixed. The problems detected in Site B included a lack of thermostat setback, excessive use of lighting during occupied hours as well as RTU short cycling and under-economizing. The total possible annual savings is 9% for Site B. Engineering analysis of the raw data was performed to demonstrate the effectiveness of the diagnostic algorithms. This trend analysis verified that the software correctly identified problems for Site A and Site B. Two illustrative examples follow

Example 1: The analysis software identified the presence of a lighting fault during occupied hours. Figure 5a indicates that lighting is on from 8:00 am to 17:00 pm, and this lighting condition repeated for all the weekdays during the monitoring period. Thus, the trend log from the lighting sensor shows the excessive lighting during the daytime and confirms the software output.

Example 2: Figure 5b shows the RTU cycling on and off very frequently during 13:15 pm–14:10 pm on September 11, 2014 (19 cycles in 55 minutes), and the same symptom repeated several times in the monitoring period. The trend log clearly shows the presence of a short cycling fault, and this is consistent with the software output.

CONCLUSIONS AND FUTURE WORK

The RCx sensor suitcase described in this paper provides a turnkey hardware-software solution to enable cost-effective, monitoring-based RCx of small commercial buildings. This technology will allow the industry to achieve small-building RCx at scale in three ways: (1) by enabling those lower-cost personnel without engineering expertise to identify energy-saving operational and comfort opportunities and associated cost impacts, (2) by offering commissioning providers the means to streamline existing processes and reduce costs, making it possible to expand their market to smaller buildings, and (3) provide opportunities for new providers to enter the market of providing RCx services exclusively to small buildings. The first field tests were successful. The hardware provided sufficient data for the software analysis, and the software gave meaningful and reasonable results. For the next step, we plan to perform further field tests to validate the robustness of technology performance. We also intend to move suitcase from its current lab-developed proof-of-concept prototype to a market-ready, commercially available product.

ACKNOWLEDGMENTS

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