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Towards a Scalable Model for Smart Buildings

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ABSTRACT

Smart, internet-connected buildings present great opportunities to scale operational energy savings. Progress is evident, with several software companies introducing new products over the last decade offering abilities to access, store, visualize, and analyze utility meter and building automation system data. Yet the rate of growth in advanced optimization has been slower in buildings applications than observed in other areas. The authors argue that efforts to deploy smart analytics in buildings are substantially hindered by four barriers specific to the sector: proprietary data architectures and communication protocols, low-performing legacy hardware, lack of contextual information (metadata) for data, and poor data quality. Based on deployment experience in a campus building portfolio of 1.6 million square feet, the authors present approaches to overcome these four barriers in order to increase the scale of potential energy savings and facilitate widespread adoption of smart building capabilities.

Introduction

Smart, internet-connected buildings present great opportunities to scale operational energy savings. For example, low-cost distributed sensor networks within a building can provide a granular indicator of occupancy and needed building services (Labeodan et al. 2015), while optimization algorithms can ensure that needs are met with minimum energy use (Blum and Wetter, 2017). As another example, data from a building automation system (BAS) can be analyzed to identify faults and to diagnose solutions (Granderson et al. 2017). Finally, an energy management and information system (EMIS) can make building energy use data easily available to operators and occupants as a means to encourage energy-saving behaviors (Granderson and Lin 2016, LBNL 2015).

Scale represents an ability to generate energy savings with fewer resources by leveraging operational data. For example, manual operation of a boiler plant by an operator to provide heating and manage energy use is an example of limited scale. An ability to monitor boiler plants remotely across a distributed building portfolio, to apply analytics that identify faults, and modify operating parameters automatically represents a greater scale and ability to manage operations or save energy. An imagined state in which any boiler plant, regardless of manufacturer and installation detail, could interact with an application ecosystem has the potential for broad scale. For example, a third-party application could determine heating needs based on data collected through occupant cell phones and relay that information to associated building systems.

Industry progress is evident, with increasing availability of hardware and software solutions over the last decade that include abilities to access, store, visualize, and analyze utility meter and BAS data (Granderson et al. 2009, Kramer et al. 2013). Yet the rate of growth in smart analytics has been slower in buildings than observed in other areas. Less than 15% of buildings even have building automation systems (Fernandez 2017) and market surveys of EMIS and related systems typically include tens of available systems rather than hundreds or thousands

(Kramer et al. 2013, Granderson et al. 2017). New, energy-related internet-enabled software solution offerings in the commercial building space may number in the hundreds. For comparison, the expansion of the smartphone ecosystem represents evidence of widespread scale. Over the last decade, the Apple store, which opened in 2008, has grown to host more than 2.2 millions apps available for download (Statistica 2018a, as of January 2017). These apps rely on hardware that is continuously updated: more than 1.5 billion smartphones were sold in 2017 alone (Statistica 2018b). Could smart buildings proliferate as have smartphones?

Barriers

While software solutions for buildings are expanding, many factors limit the proliferation that is exemplified by smartphones. We discuss four areas that present particular barriers to scaling advanced optimization in buildings: proprietary data architectures and communication protocols, low-performing legacy hardware, lack of contextual information (metadata) for data, and poor data quality. These barriers are often present in a typical university or corporate campus that may have automated building control and monitoring, but does not have a consolidated EMIS solution that meets all needs. This typical campus, presented conceptually in Figure 1, would have at least one BAS and may have several. Meter data could also be collected in an online system outside of a BAS. Some newer "smart" devices may have a connection to an enterprise or cloud-hosted server, while other meters may not be integrated. The commonality is that each data collection system represents a separate "silo" in which data is collected, labeled, stored, and used differently.

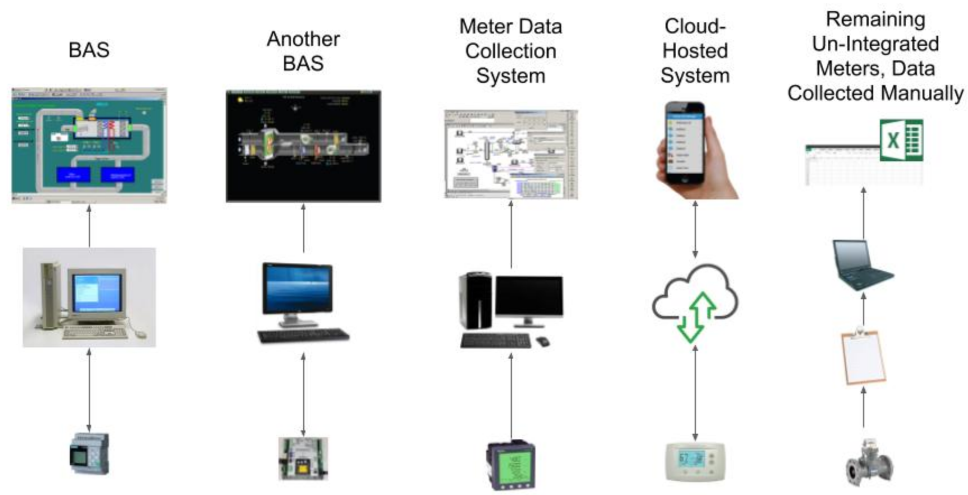

Figure 1: Conceptual representation of a siloed EMIS architecture typical of a campus environment using traditional building automation systems

Proprietary Data Architectures and Communication Protocols

Although the transition from pneumatic to electronic building automation systems coincided closely with the introduction of mass-produced personal computers and smartphones, the evolution of connected building automation technologies has significantly lagged behind the rapidly growing tech industry. Building automation systems are so deeply entwined in the physical infrastructure of facilities that installations typically remain operational for more than fifteen years. With consistent, reliable operation being a fairly universal priority across the facility management industry, reputable products with a broad support base are preferred over innovative new technologies. The BAS industry has molded to the priorities of its customers, focusing on creating products that are rugged enough to operate for years in harsh environments and implemented broadly enough to have established widespread service networks. As such, many major automation platform generations slowly evolve over decades, leaving much of the existing building stock using automation components developed prior to widespread adoption of interoperability standards such as the BACnet communication protocol, which enables digital communication between devices from different vendors.

Modern standards for BAS architecture define a three-tier design installed across the enterprise, building, and equipment levels (ASHRAE 2015), as depicted in Figure 2. Building operators interact with a BAS at the enterprise level through a user interface (UI), which may range from a text-based operator terminal to an animated graphical interface on a handheld tablet. The enterprise interface utilizes the infrastructure at the building tier to collect and display information from the equipment level deployed throughout a facility. Field devices at the equipment level act as hardware interfaces between building equipment and sensors or actuators. Although most legacy BAS conform loosely to this three tier design, capabilities of each tier vary dramatically from product to product and generation to generation.

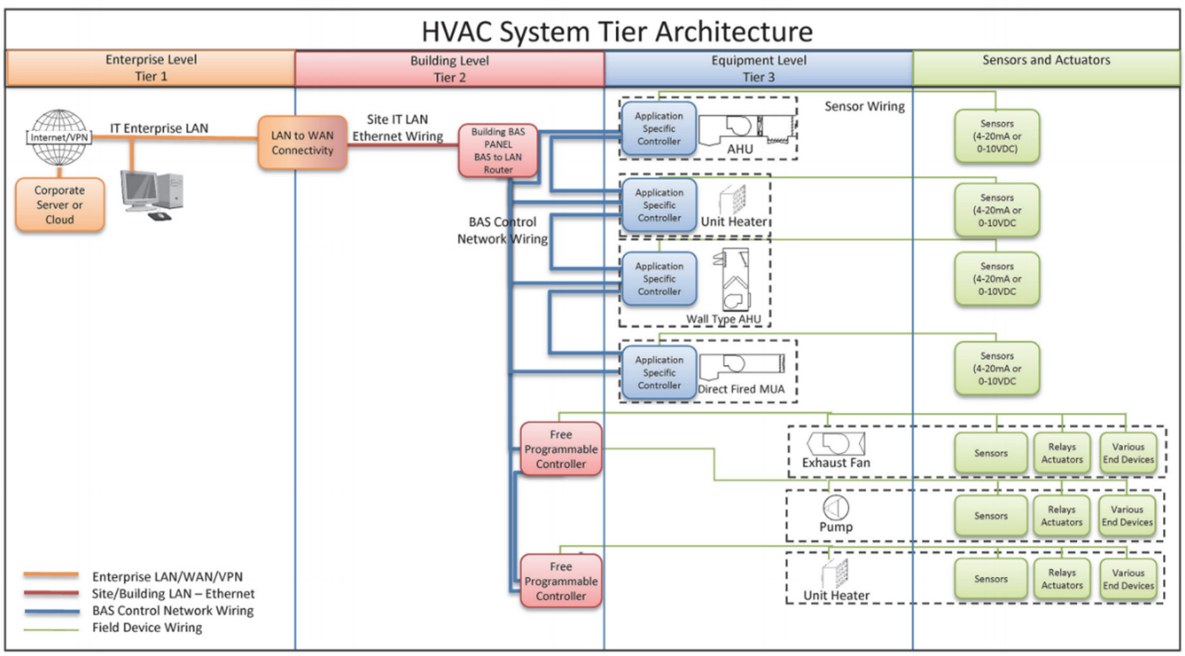

Figure 2: BAS tiers for HVAC control and monitoring (Source: ASHRAE 2015)

Due to the extreme heterogeneity of components in existing buildings, it is common for property owners to operate multiple incompatible BAS across their facility portfolios. Often categorized as assets instead of information sources, the burden of aging systems tend to be undervalued in strategic planning and left in the domain of operations personnel. As a result of this slow market growth and low prioritization of energy performance management in existing buildings, maintenance staff end up with decades-old proprietary, stand-alone systems as the interface to complex algorithms that control the operation of mechanical and electrical components in their facilities. Access to data from these systems is generally limited, prioritized for operational control rather than monitoring or visualization.

Low-Performing Legacy Hardware

Building automation systems employ specialized electronic hardware devices at both the building and equipment tiers that are shown on Figure 2. These devices provide connectivity as well as processing capabilities to store and execute program logic that constitutes equipment sequences of operation (SOO). SOO are control actions that need to be taken to coordinate the operation of building systems (for example, the ramp up of a heating system in the morning, with its associated fans, valves, and dampers). While the electro-mechanical capabilities of automation hardware have evolved at pace with the electronics industry, legacy BAS are often "left behind" in a state of disrepair. Sensors become inaccurate over time and motorized actuators stop functioning. Building operators triage the most important system components while waiting decades for the next major renovation and technicians knowledgeable of the obsolete BAS components retire long before the systems they installed are replaced. Modification and repair of legacy systems are difficult, as the availability of vendors with product-specific knowledge diminishes as manufacturers release new product generations.

BAS hardware is buried deep within the physical infrastructure of a building. In a typical office building, wiring for sensors, actuators, power, and communication spider through the walls and ceilings, across the roof, and through tight mechanical spaces. Sensors are installed on the walls and ceilings of offices and more complex spaces such as laboratories and direct the operation of motorized dampers and valves that are hidden overhead. The effort required to replace a BAS controller and its peripheral field devices is significantly more labor intensive and disruptive to the occupant than a comparable replacement of the computer and peripherals at their desk.

Most BAS software applications used to program control logic are unique to each manufacturer's product line, and rarely compatible between product generations. Modifying an existing SOO sequence requires a thorough understanding of unique logic structures, and unique equipment, sensor, and actuator configurations. In practice, this means technicians spend significant time naming sensors, developing graphical user interfaces, writing custom logic, and commissioning software that cannot be reused for other buildings or in future BAS upgrades. Despite industry efforts to adopt communication standards that promote interoperability, the lack of machine-to-machine tools and resources that would enable developers to create associated software applications, known as Application Programming Interfaces (API), prevent exposing standardized SOO and make software integration and upgrades difficult.

Lack of Contextual Information for Data

A third barrier is the lack of appropriate contextual information for data. The set of data required to fully describe the function, role, and the relationship of a point (such as a sensor or actuator) with other points or entities is often called metadata. Metadata is the data describing the data. The main issue in many BAS is that the metadata for monitoring points is not consistent and lacks semantic structure. The inconsistency is caused by the absence of a universal vendor-neutral schema, the lack of constraints in the BAS software, and the fact that the point names are manually input in an arbitrary manner by multiple, uncoordinated technicians.

One consequence is that operators waste time searching for data and have difficulties understanding the function of sensors found in user interfaces. The problem becomes particularly serious for large campuses where the number of points exceeds the hundreds of thousands. Further, lack of complete information about the function of a point (for example, what other pieces of equipment are associated with a sensor) represents a problem when a BAS is upgraded or replaced. Mapping the sensors to the new system requires a manual, labor intensive, and error-prone process. To fully map these points, designers may need to gather information from field surveys, antiquated BAS interfaces, and mechanical drawings or related documents which are typically outdated. Table 1 shows some examples of inconsistent and incomplete naming conventions used for one type of sensor collected by the authors.

Table 1. Examples of names used to identify the same sensor type across different BAS

Examples of Names for Discharge Air Pressure Sensors		
BAS Implementation 1	BAS Implementation 2	BAS Implementation 3
ACAD.AHU1.Supply Air Pressure	15 AHU 1 SA PRESS	30_ahu-001/dstpr
BJ1.AHU1_2.SSP	015-AHU-008.DA1-P	30_bl-023_024/statc_press
GIEDT.AHU.AHU1.SSP1	AHU00150.SA4-SP1	33_ahu-01/stat_press
GHA.AHU1.FAN SSP	70_BL184.DS-P	59-ahu_001/control_pressure
BRIG.SF1A.SUP STATIC	77 AHU 7 SA DUCT PRESSURE	59-ahu-004/da_stat_press
GBSF.AHU3.SPD	86 BL5-DP	
CHEM.AH2N.DUCT STATIC	90_BL4-5.DUCT-DP	

The use of appropriate metadata is also important when software designers want to encourage a more general and scalable approach to write SOO or analytics. For instance, many BAS vendors already provide code templates to implement standard SOO, which promotes standard naming conventions in programmable controller logic. Unique equipment configurations, customer specifications, and a need to apply templates across identical pieces of equipment often require the designer to add new BAS points that were not included in the original code template or to rename existing points to associate them with specific equipment. The customization process often leads to inconsistencies and deviations from standard naming conventions. On the other hand, using standard names limits the ability to add important contextual information, necessary to describe a specific system.

Poor Data Quality

Finally, problems with building sensor and meter data quality are widespread. Typical meter and sensor data quality problems arise from a wide range of failures, summarized in Table 2, in which data is incorrectly measured, missed, or misinterpreted. One overarching observation is that meter data collected through building automation systems is subject to multiple points of failure, many of which occur simultaneously. A second observation is that these issues are not easy to fix, as most problems associated with incorrectly measured data require field personnel to troubleshoot and resolve. For example, an electrician may be needed to identify or fix a problem with incorrectly installed current transducers, problems associated with missed data may require information technology (IT) professionals and/or BAS vendors to resolve, and problems with misinterpreted data may require a controls engineer to sift through BAS hardware and software configurations. A final observation is that it is difficult to optimize the operation of a building with poor data quality. It is not uncommon to spend months or years after a new building EMIS is installed working on data quality problems in order to get to the starting point of realising value from monitoring or analytic functionality.

Table 2. Multiple points of failure for building meter data

Failure	Type of Data Quality Problem	Example	Type of Person Required to Fix Problem
Incorrect meter installation	Incorrectly measured data	Current transducers are installed on the wrong wires and produce erroneous readings	Electrician Metering Vendor
Sensor inaccuracy	Incorrectly measured data	Sensor calibrations drift over time leading to invalid data (bad data that is not obviously bad)	HVAC Technician BAS Vendor
Mis-specified meter	Missed data	Metered data falls below the meter reading threshold and is not recorded by the meter	Design Engineer Facility Engineer Metering Vendor
Incorrect database settings	Missed data	Database permissions or firewall configurations prevent transfer of data to the database underlying the building automation system	IT Database Admin BAS Vendor
Mis-configured field controller	Missed data	Hardware devices in the field that collect meter data for a building automation system have insufficient memory allocations, data is overwritten and lost	Controls Engineer BAS Vendor Integration Vendor
Incorrect application software settings	Misinterpreted data	Units and meter multipliers in the building automation system that receives the data are not configured correctly and the reported data does not match the measured data	Controls Engineer BAS Vendor Integration Vendor
Incorrect historian software settings	Missed data	A point is not configured to be stored, even though the data is successfully collected by the building automation system	Controls Engineer BAS Vendor Integration Vendor

Solutions for Achieving Scale

This section presents solutions to overcome each barrier and achieve scale. These solutions are suggestions by the authors based on implementation experience at Lawrence Berkeley National Laboratory (Berkeley Lab), which operates on a campus in Berkeley, California. This campus comprises 1.6 million square feet of built space and has been built incrementally and renewed over a more than eighty year history. The building data systems at Berkeley Lab reflect all four barriers to scale discussed in this paper, even though Berkeley Lab has implemented numerous improvements to its building performance data architecture and facility monitoring and control systems over time. This has included deployment of off-the-shelf hardware and software solutions as well as custom solutions developed in-house. For each barrier, the implementation progress at Berkeley Lab to overcome barriers is presented, followed by the suggested solutions for achieving scale.

Implementing a Structured, Open Data Architecture

Data architecture barriers at Berkeley Lab have been progressively addressed over the past three decades. The building control systems at Berkeley Lab span multiple vendors and multiple generations, and have historically been siloed, with product-specific workstations scattered across the campus. When building equipment has been replaced or space is renovated, a modern BAS panel has often been installed to support the new equipment, that operates uncoordinated with the legacy BAS in the rest of the building. The energy management team at Berkeley Lab has worked to gain access to building data using various methods. The general approach has been to:

- Require BACnet or modbus communication protocols for all new equipment and BAS installed on site, enforced through construction specifications.
- Install Tier 2 (network level) protocol gateways to convert legacy BAS communication protocols to BACnet/IP. This allows for significant portions of the buildings to be consolidated into modern web-based interfaces.
- Integrate to BACnet- and MODBUS-enabled field devices using commercially available hardware and software products such as Vykon JACE, Kepware KEPServerEX, and SkyFoundry Skyspark, as well as open-source Python libraries to bridge Tier 2 BAS devices to the Tier 1 enterprise level for visualization and analysis.
- Mine time-series data from existing enterprise applications using SQL queries and APIs, and store in time-series optimized databases such as SkyFoundry Folio and InfluxDB by InfluxData. At Berkeley Lab, two separate central data warehouses have been established for building performance data to support operational and research needs.
- Develop a cross-database data access tool (API Tool) that enables data access from multiple databases, connects to different APIs in different systems and normalizes the time-series data in a standardized format. The tool, written in Python and running in Jupyter notebooks, has been used to deploy custom data analysis such as regression-based energy baselining.

The following solutions are suggested to achieve scale:

- **Use standard communication protocols.** Use open communication protocols such as BACnet, so that hardware from different vendors are able to coexist and interact in the building and equipment tiers (see Figure 2). For instance, a third-party controller can read or write data to a field device such as a rooftop air conditioning unit with factory-packaged controls, and coordinate SOO with third party systems, such as aggregating signals from multiple field devices for setpoint optimization (for example, adjusting a discharge air pressure setpoint based on the position of the dampers it is serving).
- **Use standard and open-source programming languages.** Frameworks supporting Python or Java applications, for example, instead of custom and proprietary tools can allow the building industry to benefit from a larger developer pool and take advantage of software innovations led by the IT sector.

- **Integrate to multiple data sources.** In order to integrate disparate vendors and product lines, use integration gateways that can communicate using both proprietary and open protocols to a large number of products from different vendors. These solutions can be applied to create a consistent communication layer for connectivity to new enterprise applications. Some EMIS vendors have developed such capabilities, with an ability to integrate to a wide range of data sources from multiple vendors. These hardware and software products enable interoperability across data sources and provide a means to break free from closed software systems built on top of proprietary data collection pathways.
- **Consolidate information into a flexible data warehouse.** Use commercially available data warehousing products to store data for use across the enterprise. Explore products geared to buildings that feature an integrated development environment (IDE) that enable applications to be created catering to your specific needs (see Skyspark by SkyFoundry). Also look for databases optimized for time-series records (see InfluxDB) for significantly-improved performance compared to relational databases such as SQL.The products selected should include an Application Programming Interface (API) that will enable external applications to interact with the data stored in the warehouse.

Deriving Value from Legacy Hardware

A majority of the BAS components in the buildings at Berkeley Lab are still functioning after more than 25 years of continuous operation. Actuators and sensors are replaced by in-house staff as needed, conduit and wiring installations are rugged, and control panels are well built. A variety of integration methods have been used to enhance operating sequences and user interfaces without replacing the physical hardware in the buildings. In 2002, an energy efficiency upgrade project replaced the control logic and implemented a graphic user interface for much of the campus by replacing the Tier 2 network level controllers (Barrington LanSTARs, circa 1991) with a modern equivalent (Johnson Controls NCMs), using custom protocol integrators to translate between the proprietary languages of the two different products. Recent efforts have integrated Tier 3 hardware to modern BACnet BAS platforms using protocol integrators (Sierra Monitor Field Servers) with drivers developed by Chipkin Automation Systems to implement updated SOO using the same physical infrastructure that has been in place for decades.

Although integration techniques can enhance controllability and accessibility of legacy BAS, it is important to evaluate and plan for potential consequences. While modern BAS distribute control logic across Tier 3 field devices, Tier 2 integrations consolidate the logic into a single controller and depend on digital communication protocols for execution of equipment SOO. This architecture introduces latency into signal processing, as well as single points of failure that can affect entire systems or buildings. To avoid these pitfalls, equipment that is critical for operation or data collection is provisioned with new BAS components at the Tier 3 control panel level. This approach utilizes existing control panels, wiring, sensors and actuators while replacing only the logic controllers with modern components.

The following solutions are suggested to achieve scale:

- **Interface legacy hardware with modern technologies.** Although the physical components of a BAS, sensors, and actuators often remain static throughout the lifecycle of building systems equipment, new automation controller processing technology can be retrofit to enable significant enhancements to SOO performance.

- **Consider incremental upgrades for high-priority equipment.** Advanced monitoring and SOO can be implemented through selective hardware upgrades by prioritizing major equipment and integrating to ancillary systems. For example, an air handling unit (AHU) could be upgraded with a new BAS controller, while the zones served continue to operate on legacy BAS components. Protocol integration enables the AHU logic to receive feedback from the zones for setpoint modulation.

Standardizing Contextual Information

After integrating several systems and developing two central data warehouses at Berkeley Lab, it became clear that data belonging to different BAS did not have consistent naming conventions and such inconsistency made it difficult to search, understand, and use the data. To overcome this issue, Berkeley Lab has been implementing Haystack tagging (Project Haystack 2018) for both central databases. The team has also developed a custom Python tool to quickly and automatically map thousands of sensor names into standardized tags. The Metadata Tool searches for patterns in the names and descriptions, infers relationships between components, and identifies missing sensors for each piece of equipment. At Berkeley Lab, the tagging effort has been reduced by developing metadata only for the sensors necessary for data analytics, instead of all of the trended data available from the BAS. Additional points will be imported as needed, using the same tool. This incremental approach also allows opportunities for feedback and making corrections and improvements to the metadata scripts with a minimum of re-work. Berkeley Lab is also developing new specifications for metering, integration methods, naming conventions, addressing conventions for new buildings and large retrofit projects.

The following solutions are suggested to achieve scale:

- **Use standard metadata conventions.** Some commercially-available software packages have already implemented flexible, yet standardized metadata (also known as "tagging") schemas to capture building metadata that goes beyond naming conventions (see Project Haystack 2018). Other metadata schemas developed in academia (Brickschema 2018) are also gaining traction in industry (ASHRAE 2018). Broad adoption of these standard schemas enable analytics applications that can be applied to multiple buildings with just a simple configuration step, increasing software portability[1].
- **Develop automated tagging scripts.** Mapping points to standard metadata is a time-intensive and error-prone task. Scripts that use text-matching "regular-expressions[2]" or machine learning (Bhattacharya 2015) can significantly automate the mapping of contextual metadata to integrated data points (for example, information extracted from BAS interfaces), reducing cost and increasing scalability.

Improving Data Quality

Easy visualization of building performance data can unlock its value, but it also makes data quality problems more apparent. In order to view whole-building electricity, natural gas, and water consumption across a broad range of data sources in one location, Berkeley Lab implemented two EMIS (Lucid BuildingOS and Skyspark) that allow easy access to a wide range

[1] Portable applications are "written once and can run anywhere."
[2] https://en.wikipedia.org/wiki/Regular_expression

of data from different sources and use two off-she-shelf business intelligence tools (BIME and Google Data Studio) to visualize structured data. With increased access to data, Berkeley Lab also implemented regular reporting and processes to view and analyze building performance data. As data quality issues are discovered, the root cause of the issue is investigated. Sensors, actuators, and meters are continuously validated to improve data quality.

Berkeley Lab also developed a Data Cleansing Tool written in Python and running in Jupyter notebooks that assesses data quality and enables cleansing of invalid or missing data. The Data Cleansing Tool utilizes the API Tool (described above) to collect meter data for a given time period and analyze the data to return a characterization of data quality. The output indicates how much of the data are missing (no value), have a value of zero, or have a negative value. The user has the option of manually replacing erroneous or missing data or using the tool to do so. The Data Cleansing Tool creates a regression model based on the actual baseline meter and weather data and can replace missing or erroneous data with the value from the regression model to create a continuous data set. Both the original and the corrected data sets are stored since both data sets may be useful to different audiences.

The following solutions are suggested to achieve scale:

- **Visualize data to find data quality problems.** Use off-the-shelf business intelligence tools to connect to a wide range of structured data including spreadsheets, web-based APIs, and enterprise databases. Set up standard reporting and then focus on improving the data quality for reports.
- **Proactively assess data quality.** Recognize that meter, sensor, and actuator data will have quality problems. Assess the extent of data quality issues for a set of standard reporting. Determine the root causes the data quality problems and plan for time to improve data quality.
- **Resolve metering problems in the field.** Invest the resources necessary to resolve meter data quality problems wherever it may occur in the data path from the meter in the field to the online monitoring systems. Whether through service contracts or in-house staff, sensors and actuators should be inspected, calibrated and repaired on a continual cycle.
- **Consider new solutions for data collection.** Not all data needs to travel through the BAS system. Radio networks and low-power wireless communication technologies such as ZigBee and Bluetooth LE can enable cost-effective data collection directly to the central data warehouse (Ahmad et al. 2016). These new data collection systems can have fewer points of failures than in the data collection pathways typical of BAS.

Conclusion

Progress in smart buildings is happening and there is reason for optimism in its potential to scale energy savings in the building sector. New technologies allow increasingly cost-effective collection of data that can enable optimization with increasing sophistication. However, there is also reason for caution, given the many barriers reviewed in this paper associated with legacy BAS in the building sector. The challenge now is to create value out of new technologies and new data. It will be important to deal with a transition from legacy BAS and to apply techniques that are working at scale in the IT sector in order to realize the full potential of smart buildings.

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