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Abstract

Buildings consume about 40 percent of total national energy use, are responsible for the same percentage of greenhouse gas emissions, and account for about 70 percent of electricity use. To address energy security issues and environmental concerns there is an urgent need to develop techniques that greatly reduce energy use and peak electric power in buildings while providing or improving service. One of the greatest opportunities to address this need is to accelerate the development and deployment of advanced building energy information and control systems that improve energy efficiency. These information and control systems need to be responsive to demands and dynamic prices from the electricity grid by modifying electric loads during operations, while meeting needs of building occupants. This paper reviews progress in each of these areas and suggests how future integrated control systems should be designed and operated to ensure that buildings are both efficient and demand responsive for optimal low-cost operations.

I. Introduction

Buildings consume about 40 percent of total national energy use, are responsible for the same percentage of greenhouse gas emissions, and account for about 70 percent of electricity use (D&R International, 2011). To address energy security and environmental concerns there is an urgent need to reduce energy use in buildings. One of the greatest opportunities to address these need is to accelerate the development of advanced building energy information and control systems that can improve energy efficiency and automatically respond to dynamic electricity prices by managing electric loads during operations.

This article provides an overview of research on intelligent energy information and control systems. Topics include advanced simulation for model-based control to estimate energy implications of control actions and optimization, and model predictive control to augment these models with dynamics of building systems and prediction of future disturbances and inputs. We also summarize recent research and deployment activities related to automated demand response communications and control. As supply and demand-side systems become more integrated there is an opportunity for buildings to respond to common grid signals and model-based control will help manage their response. We outline emerging systems, describing three tracks of research, each with different levels of commercialization. We discuss how these technologies need to be integrated into a modular building control operating platform. Since these systems are initially deployed in larger buildings with professional energy managers, we emphasize applications for commercial and institutional buildings. The techniques will be applied to smaller buildings as price points for deployment are reduced over time.

The article is organized into three remaining sections. The first discusses problems associated with energy efficiency in building design and operations, as well as issues with the electric grid and the need for demand response. The second discusses research conducted at a national laboratory to evaluate methods to include continuous energy measurements in feedback and control systems; this portfolio of work links energy information systems, automated demand response, and model predictive control. Finally, we conclude with a summary and discussion of future directions.

II. Energy Issues in Design, Operations, and Grid Integration

In this section we outline four key factors that influence the design and operations of buildings. These are:

- Prioritization of low first costs in building design
- Lack of simulation tools and models for performance evaluation of control sequences in design and operation
- Low energy costs, and the lack of dynamic price signals and hourly data to integrate with the electric grid
- Lack of communications and database systems

It is useful to identify why existing practices result in energy-intensive buildings. One technique is to consider the design and operations lifecycle. Two design criteria used by owners and architects to evaluate new building designs are first cost and aesthetics. Little attention is given to energy performance goals or criteria. Energy performance requirements in building codes vary, and building systems are often specified to be minimally compliant.

Another reason for high energy use in buildings is the lack of tools and models to assist in co-design and operation of energy and control systems. Many building systems such as insulation levels, window properties and HVAC sizes are developed using rules of thumb. Even more problematic is the issue that once designed, there is no reference design for how to operate common or complex systems. As we develop low-energy buildings, the need for models to evaluate low-energy control is more urgent than ever. Whole building simulation models are sometimes used in design, but rarely used to assist in operations and they are hard to use for development of control sequences for reasons described below. There is a need to develop tools for co-design of energy systems, control sequences and to support operations.

Not only are first costs a major concern in design, but energy costs themselves are low and provide limited motivation for efforts to reduce energy use. The dominant costs for an office building are labor costs for people. Another factor is the lack of time series data, which limits understanding of daily energy patterns. The majority of buildings only have access to monthly utility bills, which provides minimal information on how energy is used over time. Data of electric load shapes, temperatures and flow rates are becoming available and the uses of these data for efficiency and demand response are fundamental elements of good operations.

Throughout much of the United States peak electric loads have been growing faster than base loads. Peak loads cause stress on the electric grid causing the need for more capacity, and larger transmission and distribution systems. While this expense is seen by utilities and wholesale markets, there is a lack of dynamic price signals for consumers to incentivize them to reduce peak demand. Demand response (DR) is an area of demand side management that has four key benefits. *Participant financial benefits* are bill savings and incentive payments earned by customers who adjust their electricity use in response to time-varying electricity rates or incentive programs. *Market-wide economic benefits* are reductions in wholesale prices as DR averts the need for operating costly peak generation units. Over the long term, sustained DR lowers aggregate system capacity requirements, allowing utilities and other electricity suppliers to build less new capacity. *Reliability benefits* are operational security and adequacy savings as a result that DR lowers the likelihood and consequences of forced outages that impose costs and service interruptions on customers. *Market performance benefits* refer to DR's value in mitigating electricity suppliers' ability to exercise market power by raising power prices above production cost.

Following the electricity crisis of 2001, DR experience in California showed that customers had limited knowledge of how to operate facilities to reduce electricity costs under critical peak pricing. While the lack of knowledge about how to develop and implement DR strategies is a barrier to participation in DR programs, another barrier is the lack of automation. Historically DR has been manual requiring operations staff to receive (email, phone call) and act on signals. About 15% of the time, the person responsible for responding is not present, which is an obstacle to reliable DR.

The items listed above are related in that current buildings lack integrated information systems for design, operations, energy analysis, and DR. There are no common database or storage designs for operational data, or universal standards for interoperability, resulting in limited information infrastructures to support efficiency. There is a need to organize information systems to facilitate more efficient design, since in most buildings, 10-20% of energy use is wasted as a result of incorrect operational schedules, suboptimal set points, and control problems (Mills, 2011). Although control sequences are important to reduce energy use, designers seldom specify controls sequences at a level that allows controls providers to implement the optimal design intent.

III. Integrated Energy Information and Controls Systems for Efficiency and Demand Response

In this section we outline current research and the state of commercialization of new technology to address the problems described above.

Energy Information Systems - We define energy information systems (EIS) as performance monitoring software, data acquisition hardware, and communication systems used to store, analyze and display building energy data. Time-series data from on-site meters, temperature and flow sensors, and external data such as weather feeds, are used to perform automated analyses such as baselining, load profiling, benchmarking, and energy anomaly detection. Figure 1 shows that at a minimum EIS provide hourly whole-building electric data that is web-accessible, with analytical and graphical capabilities (Motegi et al., 2003). EIS may also include submeter, subsystem, or component level data, and corresponding analyses such as system efficiencies or analysis of end uses, yet these are less common of today's typical implementations.

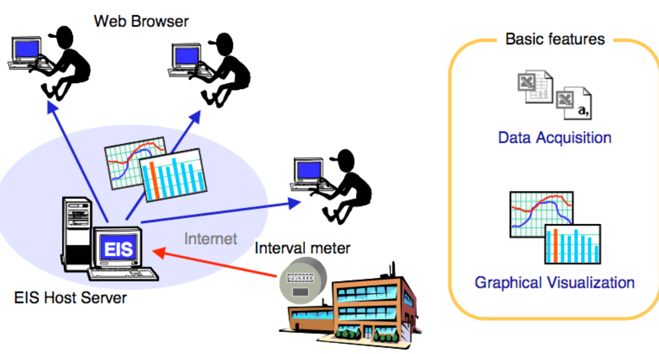

Figure 1. Basic web-based energy information system.

As advanced operational tools that provide real-time visibility into energy performance, EIS can enable a proactive approach to energy management. A growing body of evidence indicates the value of permanent metering and monitoring, particularly in the context of monitoring-based, continuous or retro-commissioning (Mills and Mathew, 2009). Also pointing to the value of monitoring, researchers have documented the positive behavioral impacts of making energy consumption visible to building occupants. EIS support trends toward benchmarking and energy performance disclosure requirements.

While EIS support the *identification* (detection) of energy waste, they depend on user expertise and depth of submetering to resolve the *cause* (diagnosis) of waste and determine the appropriate response. For example, EIS enable an energy manger to observe high nighttime loads, which might be due to over ventilation, lapsed HVAC setbacks, or poorly scheduled lighting. Case studies have shown 5-25% site or portfolio energy savings, quick payback, high return on investment, and persistent low-energy performance in cases where an organization has implemented a continuous energy monitoring and analysis program, in combination with enabling software tools and accountable staff (Granderson et al., 2011; Motegi, 2003).,Figures 2 and 3 illustrate examples of savings achieved by EIS users.

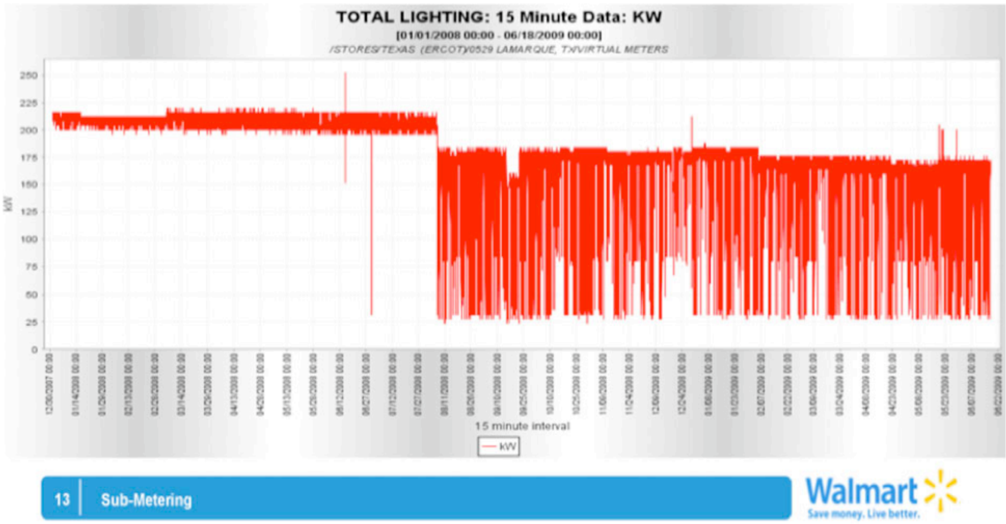

Figure 2. EIS at Wal-Mart led to identification of a 225 kW static load due to failed lighting control, and $35,000/yr in savings.

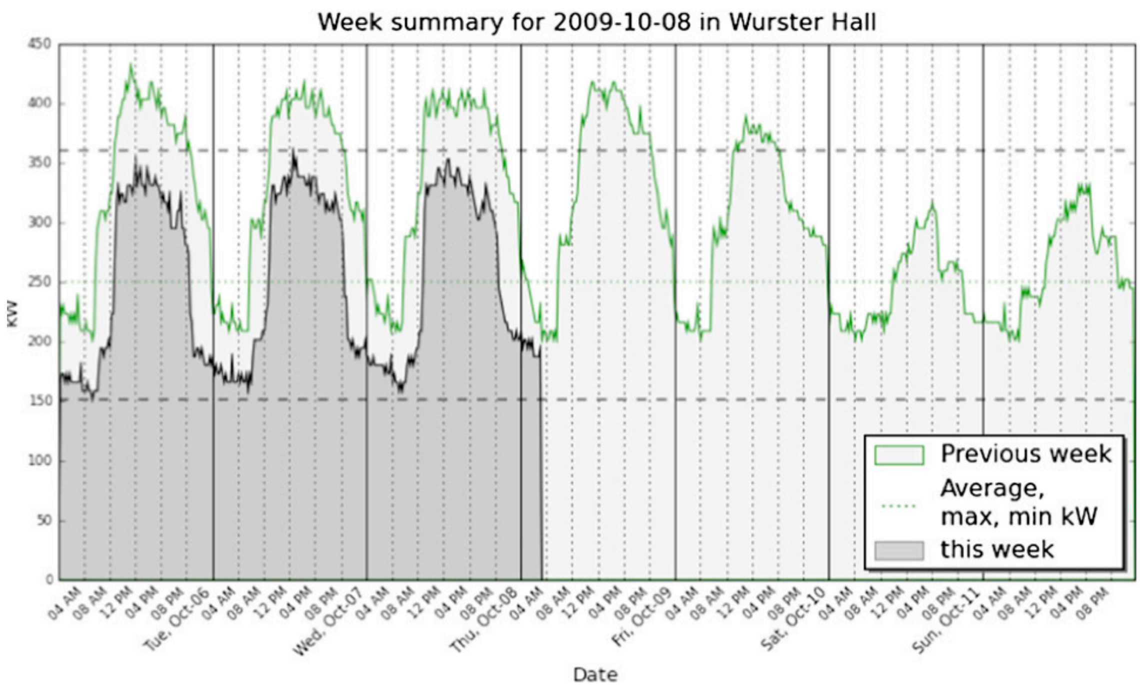

Figure 3. EIS at Wurster Hall, University of California Berkeley identified excessive loads from over-ventilation and over-illumination; correction reduced electricity use by 30%.

Although EIS are a powerful enabling technology for efficient building operations, they rely solely on statistical models of historical data to predict future loads, or identify anomalies in energy use. In contrast, tools from physics-based models compute energy consumption of individual components based on thermodynamic, heat transfer and other first principles. For example, a fan's energy consumption may be computed based on performance curves for full load operation coupled to physics-based models that correct for part-load conditions. These models can be used to automate detection of system or component faults and to identify optimal control strategies to minimize energy use. Recent research has used physics-based models of building energy use at a building in Chicago (Pang et al., 2011). Another value of these models is they can be used to evaluate future retrofits.

Automated Demand Response - Most DR programs for commercial buildings have used manual signals. Levels of DR automation can be defined as follows. Manual DR is labor-intensive, requiring a personal to turn off or change set points at each switch or controller. Semi-automated DR involves a pre-programmed DR strategy initiated by a person via centralized controls. Fully automated DR does not involve human intervention and is initiated by an external communications signal.

LBNL began research on automated DR in 2002 following California's electricity crisis, seeking sto develop a low-cost automation system that would represent electricity price signals and connect easily to existing building control systems. The concept was to use the existing Internet for the physical communications layer. From the customer side, the site's electrical load shape is modified by changes in automatically enabling DR control strategies. The technology was named "OpenADR" to distinguish it from proprietary automated DR efforts. OpenADR functions as follows. The system uses a client-server communications architecture with an open application-programming interface (API) available for development of building clients embedded in control systems that communicate over the Internet (Figure 4). The DR Automation Server, or DRAS, publishes signals from the utility, or DRAS operator, for the client. Using a "pull" client the web service requests event data from the DRAS every minute. This is a year-round, continuous system. When OpenADR signals a pending DR event, the control system prepares to participate or waits for the event and then executes a pre-programmed DR strategy (Kiliccote et al., 2010). The client sends information to the DRAS to inform the DRAS it has received the most recent signals. OpenADR systems use an XML-based web-service architecture for platform-independent, interoperable systems.

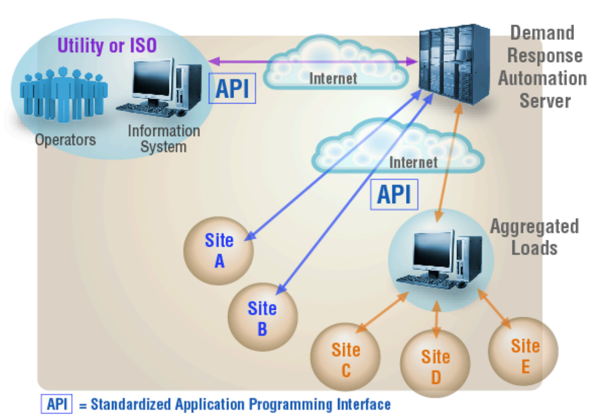

Figure 4. OpenADR client server architecture.

The above description is the most basic use of OpenADR. OpenADR is a general data model that supports a variety of price and DR mode information for both push and pull implementations. Push clients are used for fast response like those in ancillary services. The security used for the DRAS and DRAS clients addresses confidentiality, authentication, and integrity. The data communications between the DRAS and the DRAS clients within facilities is secured using Secure Hyper Transfer Text Protocol (HTTPS) and authenticated using certificates, username, and password. To maintain the confidentiality and integrity of customer information, the HTTPS uses 128-bit encryption so data are secure. Username and password authentication ensures that communications are only allowed between authenticated and known partners. The OpenADR specification, published after 6 years of field tests was contributed to the National Institute of Standards and Technology efforts on Smart Grid inoperability (Piette et al., 2009). OpenADR version 2.0 will be available in 2012 following the completion of the national standards effort. (Kiliccote et al., 2010) reviews the deployment of OpenADR in California, documenting the 160 MW of automated DR installed. Recent reports by the utilities in California suggest OpenADR will be in stalled to provide over 025 GW of load within the next year. This technology is being used in several countries outside the US in Canada, Europe, Asia, and Australia.

The new OpenADR 2.0 data model offers a few improvements to OpenADR 1.0. The process for OpenADR 2.0 development was coordinated with national standards efforts and compliance testing methodologies (NIST, 2010). OpenADR 2.0 is derived from a larger set of data models developed through a formal standards development organization (OASIS, 2012) There are additional concepts named virtual top-node and virtual end-node that allow for a more flexible architecture and allowing a fuller description of different providers and consumers of DR signals. Finally, the model has additional features for continuous and real-time feedback to consider the power use and potential control of an end-use load.

Model-Based Control - Our strategy to develop models that support building controls design and real-time operation is two-fold. Through the Building Controls Virtual Test Bed (Wetter, 2011), users can close control loops across existing simulators, and connect them to control systems for two-way communication (Figure 5). Through the Modelica “Buildings” library (Wetter, 2009), local and supervisory control systems can be modeled, including dynamic response of HVAC equipment (Figure 6). These models are modular to allow subsystem models to be embedded in next-generation energy information systems and model-based control algorithms.

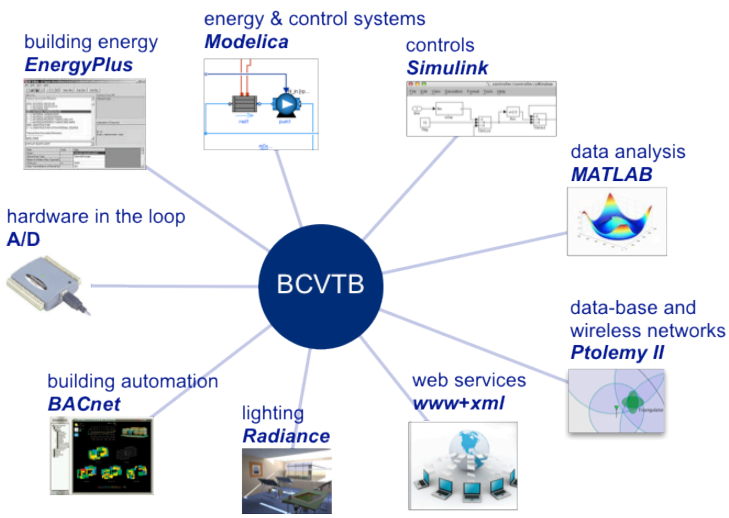

Figure 5. Building Controls Virtual Test Bed with interfaces to programs and control systems.

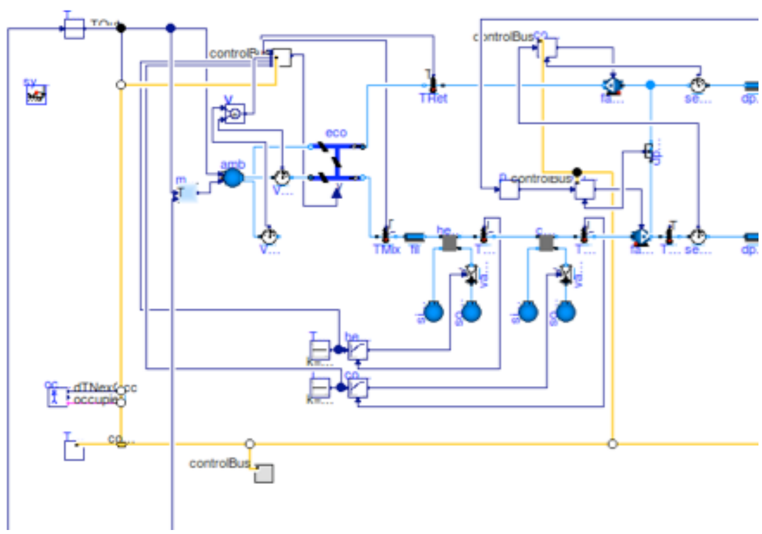

Figure 6. Partial view of a variable air volume flow system with duct static pressure reset in Modelica.

Closing control loops with the BCVTB allows, for example, the development and performance assessment of closed-loop control algorithms, implemented in MATLAB or Modelica, that integrate light-redirecting façade elements, implemented as a Radiance model, with HVAC loads, computed by EnergyPlus. This coupling across simulators and control systems has been used to develop supervisory control sequences for facades, lighting systems and HVAC systems. It has also been used for real-time performance comparison relative to a building model that represents design-intent (Pang et al., 2011).

While the BCVTB allows reuse of existing building simulation programs, the co-simulation performed with these existing programs is limited, in that data are exchanged at a user-selected time step. This makes it impractical to model closed loop controls with fast transients, because such 'stiff' systems would require adaptive time steps and implicit integrators. It also makes it impossible to properly model event-driven systems that switch the mode of operation, as this would require state-event handling. Furthermore, existing simulators such as EnergyPlus idealize and simplify controls by "controlling" steady-state models of HVAC equipment. These models are based on required power to meet set-points, as opposed to modeling feedback control loops that measure a state (e.g., supply air temperature, duct pressure) and compute an actuation signal (damper position, fan frequency) which affect flow rates based on pressure differences and actuator authority. This semantic difference between control input and output, and the lack of dynamic HVAC equipment models, makes it impractical to develop, test and specify HVAC controls in EnergyPlus.

For this reason, and to support rapid virtual prototyping of new energy systems and control systems, including model-based and model predictive controls, we developed the Modelica "Buildings" library. Modelica is a non-proprietary, equation-based, object-oriented modeling language for the modeling of complex engineered systems that may be defined by differential, algebraic and discrete equations (Mattsson and Elmqvist, 1997). The free, open-source Modelica "Buildings" library contains dynamic simulation models for air-based HVAC systems, water-based heating systems, controls, heat transfer among rooms and the outside, and multizone airflow, including natural ventilation and contaminant transport. A major difference relative to conventional building simulation is that the "Buildings" library allows implementation of realistic control sequences for supervisory and local loop control as continuous time systems, discrete time systems and state graphs, coupled to dynamic models of HVAC equipment, sensors, actuators, duct networks and buildings. These models can also be used with tools for model order reduction and controls design, as well as model-based or model predictive control. The library has been used to assess the performance of HVAC and façade control systems and for rapid virtual prototyping of innovative systems. It is also used to train professionals in fault-detection and diagnostics through the web-based LearnHVAC program. Future research will include the use of these models in real-time with fault detection and diagnostic algorithms that support energy information systems, and the use of models in real-time as part of model-based and model-predictive control.

IV. Summary and Future Directions

Historically building owners and managers have relied on monthly bills as their primary form of feedback on energy use. New tools can organize data into actionable information and automated control, enabling a continuum of integrated energy efficiency and DR, as illustrated in the framework in Figure 7. By definition, energy efficiency entails providing the highest level of service possible, for each kWh consumed; as operations move into periods of demand response, service levels may be temporarily reduced, or loads may be shifted in time. As the speed of DR increases with better controls and telemetry, the value of the DR is higher for real-time grid controls.

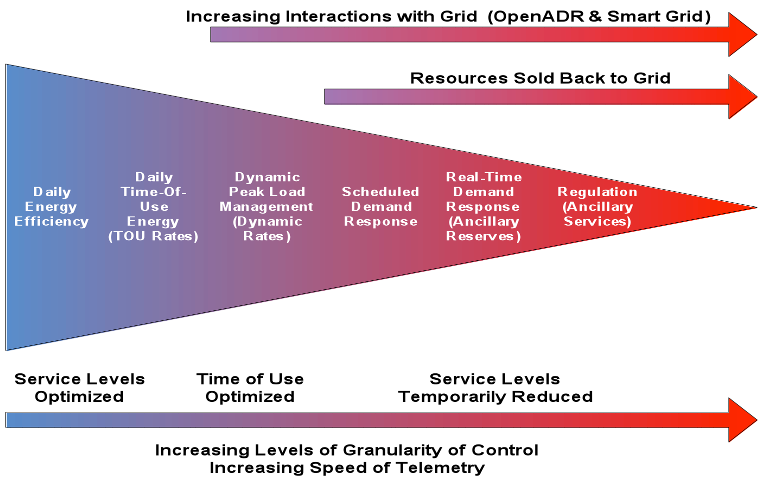

Figure 7. Linking energy efficiency and demand response.

In future *design* processes, building professionals should be able to specify and improve control sequences, test the performance of the specification using simulation, and implement and commission the control systems against the original specification. This will present a radical departure from today's control delivery process in which the designer loosely specifies the controls sequences, the controls provider implements some variant of that intent, and functional tests are not compared to the original design intent. During *operations,* building control and energy information systems will use models that account for energy use in addition to comfort requirements when computing a control action. Based on the application needs, models with different fidelity and mathematical properties will be used, offering a combination of physics-based approaches, and data-driven approaches that use measured data. These models may comprise part of a monitoring system that informs the operator about variations from design intent that may trigger re-commissioning procedures. They will also be part of model-based or model-predictive control algorithms that optimize control sequences for buildings or clusters of buildings to minimize environmental impact subject to comfort constraints, taking into account demand response signals, building-integrated energy storage, and availability of renewable energy for heating, cooling, ventilation and power generation.

V. Acknowledgements

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