# Self-Managing Cyber Physical Systems: The Case For Energy-Efficient Buildings

Increasing instrumentation of our buildings has lead to numerous new opportunities to better understand and optimize their energy consumption patterns, as well as made them a prototypical example of cyber physical systems (CPS). However, because of the heterogeneity of our building stock and the dynamic environments/functions that buildings need to operate in and support, energy conservation measures are very much building-specific and time-dependent. Hence, although there has been considerable effort put towards simplifying and automating the identification of energy efficiency improvement opportunities, because of the considerable variation across buildings, engineers still rely on various different manual activities to arrive at them through all types of energy audits. The difficulties associated with obtaining information about the configuration, status, and relationships between different building components and systems is believed to be at least part of the problem [14, 13].

Buildings account for approximately 40% of the annual energy consumption in the U.S., and similar proportions of the energy used in other countries. Commercial buildings, in particular, represent 45% of that figure (i.e., 20% of the total) [19]. There are great opportunities to reduce these numbers through efficiency upgrades, optimized operation and user engagement, as evidenced by many different studies (e.g., [9, 4]). For example, research shows that up to 40% of the energy used by HVAC systems is wasted due to faulty operation [17], so merely identifying and correcting these faults would result in a substantial reduction of the total energy used. However, even when the facilities are equipped with modern automation systems, engineers are faced with the challenge of having to manually interpret and analyze the collected measurements, which in many cases come from a variety of systems with little contextual metadata to assist in the interpretation.

In a recent review of the communication systems for building automation systems (BAS) [7], the authors conclude that there is a need for automated tools to support the integration of different systems and identify the location of the sensing nodes within a building. These set of challenges is present in many diffferent CPS, but because of the heterogeneous nature of buildings, it is particularly relevant in this domain. The integration of different building automation systems is an unsolved challenge that researchers have attempted to solve via novel middleware systems to homogenize the hardware and communication layers (e.g., [3, 10, 18, 1], or attempting to solve the schema matching problem [12, 16]. However, despite these advances, many case studies conclude that the vast majority of the data being collected by these systems today is almost never used in a proactive fashion (e.g., [5]), perhaps because of this lack of metadata and/or integration across systems. For example, hundreds of different automated fault detection and diagnosis (FDD) algorithms for heating, ventilation and air conditioning (HVAC) systems have been developed in the past few decades by researchers [11]. Yet, despite their proven ability to significantly reduce the energy consumed for HVAC, these algorithms are seldom used by facility managers due to, among other things, the difficulties associated with obtaining the information that they require [6, 8] even if it is automatically being collected by a BAS or contained in a digital information model.

Hence, there is a need to develop mechanisms by which building automation systems can automatically recognize the stimuli behind the measurements, as well as existing functional and spatial relationships between the instruments and the different building systems. Instead of relying on metadata and contextual information being available, it is important to understand how much of this information, if any, can be extracted directly from the measurements being collected. Then, once this information is known, existing automated approaches for improving the energy performance of buildings can be more easily applied.

In many applications, humans are still much better than computers at inferring content and context (metadata) from measurements, which is why generating metadata is still largely a manual process. Yet, the increasing volume of data being generated and the lack and/or limitation of standard information models to describe these measurements suggests that computerized analysis of these data will be required. Hence, it is important that we develop approaches to automatically annotate and extract meaningful content out of raw sensor streams from buildings (and other Energy CPS) for the purpose of improving their self-managing and self-improving capabilities. Metadata about building measurements is scarce and, even when there are information models available (e.g., [2]) and/or self-describing sensors (e.g., [15]) there are still a number of reasons why further analyzing sensor streams is required, including:

- **Indirect Measurements:** Sensors are usually deployed in order to infer some specific property of a physical phenomena or process in buildings, yet these properties are rarely measured directly and require that we perform inference on the data.
- **Security and Sensor Fault Detection:** Assumptions made about the sensor properties and the phenomena being monitored should be checked against the data to confirm that the sensor is providing accurate measurements.
- **Varying Processes:** Some sensors measure a variety of different processes over time (e.g., plug-level power meters measure any appliance connected to the plug), therefore requiring further interpretation of the sensor stream to identify what is being measured.
- **Aggregated Phenomena:** In some cases, sensors measure a combination of different phenomena of interest, thus requiring that the sensor stream be segmented and annotated in order to track each phenomenon separately.
- **Inexisting Static Metadata:** Basic information about the sensors, such as their location within the building, is not known and inferring this from data would drastically improve the robustness and applicability of existing CPS solutions to better manage the energy use of buildings.

Many of these challenges extend beyond buildings and into virtually all other CPS. Therefore, the solutions developed for these particular problems will have wide-ranging impacts and will significantly improve our fundamental understanding of how to design and implement CPS.

# References Cited


[1] Yuvraj Agarwal, Rajesh Gupta, Daisuke Komaki, and Thomas Weng. BuildingDepot: an extensible and distributed architecture for building data storage, access and sharing. In *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, BuildSys '12, page 6471, New York, NY, USA, 2012. ACM.

[2] Mike Botts, George Percivall, Carl Reed, and John Davidson. OGC sensor web enablement: Overview and high level architecture. In Silvia Nittel, Alexandros Labrinidis, and Anthony Stefanidis, editors, *GeoSensor Networks*, number 4540 in Lecture Notes in Computer Science, pages 175–190. Springer Berlin Heidelberg, January 2008.

[3] Stephen Dawson-Haggerty, Xiaofan Jiang, Gilman Tolle, Jorge Ortiz, and David Culler. sMAP: a simple measurement and actuation profile for physical information. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, SenSys '10, page 197210, New York, NY, USA, 2010. ACM.

[4] J. Froelich, K. Everitt, J. Fogarty, S. Patel, and J. Landay. Sensing opportunities for personalized feedback technology to reduce consumption. In *the CHI workshop on Defining the Role of HCI in the Challenge of Sustainability*, 2009.

[5] Jessica Granderson, Mary Ann Piette, and Girish Ghatikar. Building energy information systems: user case studies. *Energy Efficiency*, 4(1):17–30, February 2011.

[6] R Jagpal. Computer aided evaluation of hvac system performance: Technical synthesis report, 2006.

[7] W. Kastner, G. Neugschwandtner, S. Soucek, and H.M. Newmann. Communication systems for building automation and control. *Proceedings of the IEEE*, 93(6):1178–1203, 2005.

[8] Srinivas Katipamula and Michael R Brambley. Review article: Methods for fault detection, diagnostics, and prognostics for building systemsa review, part i. *HVAC&R Research*, 11(1):3–25, 2005.

[9] Sila Kiliccote, Mary Ann Piette, and David Hansen. Advanced controls and communications for demand response and energy efficiency in commercial buildings. Technical report, Lawrence Berkeley National Laboratory (LBNL), January 2006.

[10] Andrew Krioukov, Gabe Fierro, Nikita Kitaev, and David Culler. Building application stack (bas). In *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, BuildSys '12, page 7279, New York, NY, USA, 2012. ACM.

[11] Xuesong Liu, Burcu Akinci, Mario Berges, and James H. Garrett Jr. Extending the information delivery manual approach to identify information requirements for performance analysis of HVAC systems. *Advanced Engineering Informatics*, 2013.

[12] Xuesong Liu, Burcu Akinci, Mario Berges, and James H. Garrett,Jr. An integrated performance analysis framework for HVAC systems using heterogeneous data models and building automation systems. In *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, BuildSys '12, page 145152, New York, NY, USA, 2012. ACM.

[13] William Livingood, Justin Stein, Toby Considine, and Chuck Sloup. Review of current data exchange practices: Providing descriptive data to assist with building operations decisions. Technical Report NREL/TP-5500-50073, National Renewable Energy Laboratory, Golden, Colorado, May 2011.

[14] J. Ploennigs, H. Dibowski, U. Ryssel, and K. Kabitzsch. Holistic design of wireless building automation systems. In *2011 IEEE 16th Conference on Emerging Technologies Factory Automation (ETFA)*, pages 1–9, 2011.

[15] D. Potter. Smart plug and play sensors. *IEEE Instrumentation Measurement Magazine*, 5(1):28–30, 2002.

[16] Erhard Rahm and Philip A. Bernstein. A survey of approaches to automatic schema matching. *The VLDB Journal*, 10(4):334–350, December 2001.

[17] K. W. Roth, D. Westphalen, M. Y. Feng, P. Llana, and L. Quartararo. Energy impact of commercial building controls and performance diagnostics: Market characterization, energy impact of buliding faults and energy savings potential. Technical Report TIAX LLC D0180, TIAX LLC, Cambridge, Massachusetts, USA, August 2005.

[18] Anthony Rowe, Mario Berges, Gaurav Bhatia, Ethan Goldman, Raj Rajkumar, James H. Garrett, Jos M. F. Moura, and Lucio Soibelman. Sensor andrew: Large-scale campus-wide sensing and actuation. *IBM Journal of Research and Development*, 55(1.2):6:1 – 6:14, January 2011.

[19] Energy Information Administration (U.S.). *Annual Energy Review 2011.* Energy Information Administration, none, annual edition edition, October 2012.