My Car Is Smarter Than Your Building: 
Building Controls in an Era of High-Performance Buildings

Abstract
To meet the dual challenges of climate change and peak oil, high-performance (low-energy) buildings must be the rule rather than the exception. Typical buildings today frequently do not deliver the energy performance predicted by designers or desired by the owner. One of the primary reasons for this failure to perform is that building control systems are not designed, installed and/or operated as an integrated part of the building system. High-performance buildings have additional features such as daylighting, personal lighting controls, mixed-mode or natural ventilation and demand response. To optimize performance, controls must meet further challenges to enable these new technology and design options to respond to the needs of owners and occupants while saving energy.

With buildings using approximately 40% of primary energy in the U.S., improving building performance is crucial to achieving substantial energy reductions. The path to achieving zero-net energy buildings will typically require buildings to be 70% to 80% more efficient than standard practice today, with on-site renewable generating technologies providing the balance. These buildings will also need to continue to perform at these high levels of efficiency for their entire useful lives, which means that owner/operator feedback loops, benchmarking, flexible control strategies and ease of operation become critical aspects of the control systems.

This paper addresses current design, technology and process barriers to achieving high-performance buildings related to the current state of building controls design/selection and implementation. It summarizes the results of prior research pinpointing areas for improvement and examines the steps necessary to restructure controls in commercial buildings to achieve potential.
The Challenge
The success of high-performance or green buildings will inevitably depend, in part, upon highly reliable, effective and usable controls. Is the state of controls industry up to this challenge? The New Buildings Institute (NBI) staff relied on two major resources to examine this issue. First, NBI staff has significant experience working with control systems in a variety of commercial buildings settings, including working with California Energy Commission Public Interest Energy Research (PIER) controls-related research projects. Second, NBI interviewed 10 prominent people (see last page for the complete list) in the commercial building development, controls and diagnostics field to benefit from their experience and suggestions.1

NBI identified two major issues. First, present state-of-the-shelf controls have serious flaws (e.g., they do not typically include building performance measurement and feedback as a basic element) and are frequently inadequate to meet the needs of many conventional buildings. Second, the controls industry has yet to develop effective and reliable controls specifically for the new high-performance building systems that the market is beginning to deploy to meet climate and other environmental challenges. The reality is that we do not yet have the ability to deliver robust, flexible control systems that deliver persistent savings, let alone meet the future challenge.

Measured Building Performance and Controls
Recent studies indicate that the “as-built” performance of new buildings is often not consistent with “as-designed” predicted performance. This finding undermines confidence in building design and technologies and raises questions about building operational strategies. Additional studies indicate a substantial portion of the problem may reside in the building controls.

A 2007 study by NBI for the U.S. Green Building Council of Leadership for Environment and Development (LEED) New Construction (NC) buildings (Figure 1 below) showed a scatterplot of over- and under-achievement when compared to design intent, with some buildings showing very poor measured energy performance. The energy models for these buildings were reviewed as part of the LEED certification process; all buildings received at least basic commissioning, with many buildings achieving the optional LEED Building Commissioning point.

A typical explanation for variations from modeling results is that the building is not being operated as modeled; for example, the hours of operation are more (or less) than assumed in the model development. The lack of predictable performance could have many causes. Within the LEED study, however, any building that met the parameters was benchmarked

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1 While these conversations informed the development of this paper, the issues and recommendations included in the paper represent solely the viewpoint of NBI staff.
to generate an Energy Star Benchmark score. The benchmarking process corrects building energy use for key variables, including operating hours and percent occupied. The Energy Star benchmarking showed a similar pattern with nearly 25% of LEED buildings using more energy per square foot than similar average buildings. Given that the LEED buildings were designed to be significantly more efficient than average, and most were more efficient, how is the poor performance of some buildings explained?

One reason that EPA has focused Energy Star buildings on measured performance is that their research has indicated that the presence of energy efficiency measures does not necessarily lead to energy efficient performance. In fact, when it comes to control measures, performance is quite variable.

![MODELED VS ACTUAL SAVINGS -](image)

Figure 1. The comparison is between the modeled savings of the design vs the measured savings (from energy bills) of the real building. As can be seen on the scatter plot, over 40% of the buildings underperformed the design objective, half of those not even meeting the baseline, which for these buildings was primarily ASHRAE 90.1-1999. It should be noted that while the performance of any individual building was not easily predicted based on design, the overall group of LEED NC buildings in the study averaged approximately 30% above CBECS means.

A review of the 2003 Commercial Buildings Energy Consumption Survey (CBECS) data suggests buildings with energy management control systems fall into a bimodal distribution, i.e., there are higher percentages in both the bottom 25% (least energy
efficient) and top 25% (most efficient) of buildings than in the average, based on performance (Figure 2). These data are not based on modeled results, but rather actual building use. This pattern suggests a disconnect between the presence of an energy control system and actual delivered efficiency. This is consistent with a follow-on study of the LEED group shown above, where more than half of the poorest performing buildings had significant controls problems contributing to their poor showing.

![Figure 2. Performance of Buildings with EMS](image)

A similar bimodal pattern exists for two peripherals commonly linked to the EMS in energy efficient buildings, variable frequency drives and economizers (Figure 3 below). In fact, for economizers, there are more buildings in the lowest performing 25% than either the average or top 25%. This finding is reinforced by the results of an NBI study done in 20003 which showed 60% of all economizers five years old or newer were not installed properly or not performing correctly.

![Figure 3. Technology vs Performance](image)
In 2002, the National Building Controls Information Program (NBCIP) based at the Iowa Energy Center took a detailed look at control issues. The concern was that even conventional buildings were facing serious controls issues. In a concerted effort to identify the most significant problems facing building controls, researchers examined a database of several thousand buildings and held two roundtables of control experts. Below are two graphs from the roundtable summary document which illustrate the findings of the participating experts. The first graph (Figure 4) shows the relative frequency with which various factors play a role in control system problems. Three elements stood out as problem areas, input devices (sensors), programming (software) and operator unawareness (lack of training). Software was seen as the most frequent problem.

The second graph (Figure 5) shows the relative energy impacts of each category of problem. Here the issue was not just frequency, but also whether the problem had a small or large impact on energy waste. The results were as follows:
Again, programming is seen as a major problem. Sensor problems, which were listed as high frequency, are viewed as less significant in terms of energy waste. However, all aspects of operator behavior, even if infrequent, are seen to have significant energy waste implications, presumably because the duration of the impacts.

**Causes of Poor Performance Related to Controls**
Having identified the problem areas, the next step is to identify the root causes of these problems. In discussions with a broad range of building controls experts, a number of items consistently were cited as contributing to poor controls performance. These are:

- **Lack of performance feedback and diagnostics** - The single most important of these is a systematic lack of feedback on the performance of the systems controlled. If it isn’t measured, it isn’t managed. Monitoring and automated fault detection and diagnosis (FDD) ought to be primary control system functions. Owners, designers and building managers simply do not know how buildings are performing and, as a result, have little evidentiary base upon which to enforce guarantees, guide operations, fix what is broken or support future building and controls development. Without performance verification, there is little incentive...
to perform well on design or installation of a system. Without FDD, the causes of poor performance can not be identified and corrected cost effectively. FDD needs to be an integral part of the control system, which itself is the main supervisory system for the entire building. The control system is not just another piece of hardware like the lights and ductwork; it is fundamental to establishing and tracking the entire operation of mechanical and electrical systems. It may also have the responsibility in any given building to support fire/life/safety requirements. Currently, there is no national standard or consensus on what constitutes FDD for building control systems. While commissioning helps, it is often limited to functionality testing, not performance testing, and is often not an ongoing performance management tool.

Finally, there is an inverse ratio between the amount of automated FDD and the need for specialized user training. Systems that are intuitive and self-tuning are more user friendly. The embedded diagnostics can anticipate and respond to user inputs to compensate for lack of knowledge and/or errors. They also can provide repairs and “work-arounds” for system failures. Personal computers and automobiles are good examples of this approach in use - allowing millions to use these devices productively with a minimum of training.

- **Controls are not integrated into the building design process** - Design teams do not understand how building design decisions affect controllability nor the capabilities and limitations of controls. Design discussions rarely include building system operating strategies or performance goals, even in “green” projects. There is an assumption that “someone” downstream will take care of it. Controls contractors are usually brought in near the end of the project, when the design has been hardened without consideration of controls.

- **A lack of industry standards for true interoperability** – Even with the advent of BACnet and LonWorks®, true interoperability remains elusive. While systems technically can “communicate” using these protocols, there is no functionality standard. The controls industry has created a patchwork of incompatible, proprietary approaches that make the urgent need for standard protocols and interoperability an elusive hope. It just can’t happen under the current controls industry business model.

- **Inadequate and non-standard controls design** - Existing control strategies and standard sequences are often obsolete, more reflective of the historic past than the present capability of the equipment and software. For example, systems are typically not self-configuring, a feature that has been part of the computer industry for more than a decade. Conversely some control products are handicapped with “features” that complicate both control and diagnostics. Controls are "Balkanized" by system; that is, solutions are sought at the system or subsystem level without regard to the impacts on other systems or whole building performance. With little industry-wide standardization or “best practice,” each system is idiosyncratic.
The value of the controls is never made explicit - For decades, controls have always been one of the last systems into a building and one of the first systems on the cutting room floor of value engineering. The building owner/developer, who has to approve the controls budget, usually sees controls only as a cost. The value proposition that controls enable proper operation, verify performance, assure comfort, reduce liability, allow flexibility in use, etc., requires better articulation.

Lack of control system expertise and experience - The average engineer generally lacks specific knowledge and experience to provide good guidance on control design, specification and selection. As a result, many HVAC designers delegate the controls design to sub-contractors, “specifying” vague deliverables such as chiller optimization. Maintainability and the ability of the maintenance crew to understand, maintain and troubleshoot the specified controls are often overlooked.

The procurement process is broken - The typical procurement process for controls allows for little design team interaction and creates perverse incentives for the designer and supplier. The low budget for controls provides little markup (incentive) for the mechanical engineer, who leaves the detailed design to the vendor, who is a subcontractor to the mechanical subcontractor. Controls specifications are often written by vendors and do not provide a basis of design including design intent, sequence of control, points list and more. They provide no incentive for higher performance, but typically focus on lowest cost in the absence of design guidelines.

Little thought is given to long-term operation - Typically not considered are: 1) the maintainability of the controls themselves, 2) the value of controls for verifying and maintaining building comfort and efficiency over long haul, 3) the need for flexibility in control to meet varied conditions due to “churn” over the building life, and 4) the technical demands made on the building operator.

Training is inadequate along the entire length of the delivery chain – As discussed above, significant training is needed largely because of the lack of both user-friendly design and FDD. As a result, design professionals generally are ill-prepared on controls. Only the largest design and construction firms have trained controls specialists on staff. Mechanical and controls contractors are typically trained only on their own equipment. Building engineers often are given little or no training on the systems they operate. Generally, well-trained and experienced personnel end up being promoted out of the work force into management and sales, taking their intellectual capital with them. The problem is exacerbated by the lack of standardization in the industry, so training on one system frequently is not transferable to another.
A Useful Comparison – Controls-Savvy Cars

A useful parallel which, while not perfect, can provide some insight between the development of controls in buildings and the development of controls in automobiles. Up until the 1960’s, the focus for automobiles was on style and performance with little regard for energy consumption or related pollution issues. With air pollution becoming a major societal and regulatory issue in the ’60s, coupled with the price shock of two oil embargoes in the ‘70’s, automobile designers and manufacturers began to focus on the need for more sophisticated control to meet requirements for better pollution control and higher mileage (CAFÉ Standards) without a loss in performance.

While early efforts focus primarily on a mechanical solution (e.g., fuel injection and vapor recovery), the evolution of the computer industry gave automotive engineers one of the key tools they needed. Computerized control of the engine and drive chain throughout the whole range of operation, along with refinements in engine and exhaust design, provided the necessary advancements to meet the new pollution standards and mileage requirements while retaining or even increasing performance. Industry-wide training necessary to support this technology revolution brought a new level of competence and professionalism to the vehicle service sector.

Effect of Attribute Tradeoffs

Since the regulations applied across the board, higher performance systems provided an immediate market advantage and differentiator to leaders in innovation and quality product, driving additional improvement. As can be seen on the right hand graph in Figure 6 above, the potential efficiency improvement (green triangles) has been substantial, nearly a 14 mile-per-gallon increase since 1981 if vehicle weight, acceleration and percent manual transmissions had not been modified. The actual mile-per-gallon improvement has only been about 4 mpg because the increased efficiency was used to allow an increase in weight, performance and use of automatic transmissions.
Here we see a textbook case of the use of sophisticated controls to meet multiple market goals.

Once in place, the new controls technology led designers to realize the tremendous value of monitoring and FDD in the maintenance and operation of the automobile. The “smarts” embedded in the engine controls reduced the level of “smarts” and training needed at both the driver and mechanic level to diagnose problems and keep the engine in tune while providing a proprietary edge to branded maintenance shops. The dashboard became information and feedback center, with warning lights and gauges to alert the user of potential problems (low oil, mpg, check engine). Embedded intelligence also greatly extended the intervals between required maintenance, meaning the vehicle is on the road more and in the shop less. (For a more complete and fascinating comparison of the automobile and buildings, see Barney Capehart’s book *Web Based Energy Information and Control Systems: Case Studies and Applications.*

Perhaps the best metaphor for where the controls industry needs to go is the development of the hybrid vehicle. A few innovative manufacturers anticipated the need for substantially higher vehicle performance. They realized that to significantly notch up performance, they needed to 1) apply technologies differently and 2) integrate all elements of the drive chain and bring them under unitary control. The onboard computer control system seamlessly integrates diverse systems, including power sources, to ensure performance with economy while providing excellent graphic feedback to the operator and a high level of fault detection and diagnostics to the maintenance team. The result - a 50% reduction in fuel requirement with no special training required for the operator and increased reliability. That would be a great position statement for high performance buildings.

**Lessons Learned**

Certain lessons learned from the automotive industry provide useful guidelines for controls development:

- Setting clear performance standards, and holding both the industry and the individual unit to those standards, can lead to rapid and significant improvement.

- It is not sufficient for mechanical systems to be properly installed. The operation of the entire system must be controlled to meet the higher standards.

- Facing a need for an immediate solution to a serious threat, industry R&D must focus on identifying a few, clear and easily replicable solutions that capture the majority of the needed improvement while buying time for development of future technologies with even greater savings along with carbon-free alternatives.

- Automated fault detection and diagnostics for both the user and service personnel allows the industry to field the necessary but more sophisticated systems without an impossible training burden and ultimately at significantly less expense.
• Regulatory requirements on emissions and efficiency provide both the impetus and the level playing field for industry response.

In the discussion of controls and of vehicles thus far, we have treated them as homogeneous classes. In fact, both groups represent a wide range of types. In the case of the hybrid car, the manufacturers first focused on the simplest, most ubiquitous vehicle, the small sedan. They left the large, less numerous vehicles like trucks for future development. As a parallel in the building market, 95% of all buildings are under 50,000 sf, and these small buildings represent half of all the square feet available. While it might be more technically interesting to focus on large, complex buildings, the bulk of the market is in small, simple buildings. This is actually very good news, since it suggests a path for moving forward.

**Small Buildings** For smaller, simpler buildings, the major focus is on reliability, simplicity of installation and operation, and some limited flexibility to adapt to various building uses. In this class of buildings, control improvements have a small individual impact, but could have a very large impact on national energy use with replicability across a large number of buildings. If these buildings are networked together by the utility, they could have a large demand impact as well. For this type of building, especially for the HVAC system, the controls are typically embedded in the equipment and are potentially capable of sophisticated control and FDD although the sophistication is rarely employed. The key here is to provide an integrating platform that can make embedded controls in various systems work efficiently and work together (e.g., HVAC and lighting), while also providing the metering and communications capabilities discussed above.

**Large Buildings** For larger or more complex buildings, reliability and ease of installation are also issues, but controls characteristics such as flexibility of use, interoperability, “enterprise” level reporting, the ability to customize and “smart” operator interfaces are key to high performance. Design and performance issues are also of greater concern to individual owners because of the size of the potential energy impact on a given building. However, often the more idiosyncratic nature of the building systems and operating parameters means the solution is less transferable to other buildings and may require special expertise in design and installation.

This suggests two parallel controls development approaches:

1) A simple, reliable, standardized controls integration platform for small, simple buildings that can have a large impact by virtue of the sheer number of units involved, and

2) More sophisticated controls packages for the larger, more complex buildings that require greater customization but allow greater flexibility and have higher individual building savings.
These complementary approaches also allow for mass production/replication on the one hand and continued design development on the other, with large buildings acting as a test bed for new ideas.

**What Needs to Be Done, and Who Should Be Doing It?**

There are several trends that support improvement in building controls now. Public awareness of the need for more efficient, more environmentally benign buildings is at an all-time high. A number of large commercial real estate firms, the Building Owners and Managers Association and the State of California have all adopted policies to benchmark and improve building energy performance. Controls-related options will be a major part of their progress forward. Additionally, the focus is no longer solely on energy savings; energy demand control has become a significant issue for many utilities facing capacity constraints. In new construction, the increased market penetration of Building Information Modeling strongly supports a more integrated and holistic view of building design, which in turn supports better control design.

On the technology side, improvement in controls technology has been aggressively pursued at the research level by a small number of institutions and firms, offering potential solutions. Experience in unrelated but parallel applications for controls, such as in automobiles, has shown both the efficacy and potential architecture of robust, embedded controls systems.

As a basis for further development, NBI proposes a three-pronged approach - moving forward on regulation, technology and process simultaneously.

**Regulatory Strategies**

Regulatory approaches or government/utility incentive programs can move the building performance bar rapidly and create opportunities for controls development while providing a level playing field. Options include:

- Push for measured energy performance requirements for buildings that will spur new controls development as a low-cost way to improve building performance.
- Require real-time performance metering, basic FDD and user feedback in every building controls package no matter how rudimentary - even down to programmable thermostats. National FDD standards would define the required controls-specific elements. These could be incorporated as building code requirements.
- Consider increasing energy rates for buildings with large energy appetites relative to similar buildings in their class. A model for a regulatory approach proposed by Tom Hartman would create federal standards (similar to EPA automobile standards) that are then applied through local jurisdictions or utilities. ([http://www.hartmanco.com/pdf/a48.pdf](http://www.hartmanco.com/pdf/a48.pdf))

**Technology Development**

While the regulation proposed above sets the minimum threshold for controls capabilities, it does not address the need to rapidly accelerate the development of the next
generation of high performance controls. This is an appropriate role for government sponsored applied research. A number of organizations are presently working on pieces of what is needed (NBCIP, national labs, Carnegie Mellon University, private sector entrepreneurs), but their efforts are not coordinated and lack adequate funding.

A key option is the immediate formation of a controls “skunk works” using the brightest minds in the industry to prototype the next generation of controls. (A “skunk works” is a small, adequately funded, dedicated team whose singular goal is to produce a working prototype in the shortest time possible.) This group, which might be a public/private partnership, would be charged to develop products in three priority areas:

- Control algorithms specific to high performance sustainable systems (e.g., daylighting, lighting, hybrid ventilation, etc.), including climate-specific variations.
- Control elements that serve to integrate building operation and simplify and improve the operator/user interface, taking maximum advantage of the computerized platform to implement forward looking approaches, e.g., continuous optimization of all building systems with robust FDD.
- A standardized high performance controls integration platform (hardware, software and instructional guide) for smaller, less complex buildings, that is simple and robust, yet delivers persistent savings and contains the two elements above.

The resulting product should have strong communications capabilities, including anticipating likely “enterprise” level needs, such as utility demand response. It should be “future proofed,” e.g., be easily reconfigured or self-configured throughout the building’s life. Finally, the product needs to be fully plug-and-play to avoid the disaster of field assembly common today in component based systems.

This core set of technology and communications solutions is a “public good” that can serve as a platform for future, proprietary products while avoiding the logjam of non-interoperability.

**Process Enhancements**

As discussed above, many of the issues with controls revolve around the way they are designed, installed and operated. While regulation and the development of better controls can help alleviate these problems, the process by which controls are supplied to the marketplace remains flawed and needs revision. Some models of how to do it right, such as the California State University System Controls Procurement Guidelines (http://www.calstate.edu/cpdc/ae/gsf/documents/controls_procurement_guidelines.pdf), have emerged recently in relationship to sustainable buildings and integrated design. These successful models (and a tailored version for small buildings) need to be more widely disseminated to engineers, architects and facilities managers through standard engineering and AIA project contracts. Specific recommendations include:

- Redesign the controls procurement process to provide both the designer and the contractor with incentives for delivering a better system. For larger projects, use an
integrated design process with a clear statement of intent for control attributes and performance levels.

- Focus on measured energy performance at the design team/owner level, which will re-orient the entire chain (from owner/developer, through designer and builder, to operator and occupants) to the value of high performance controls in ensuring energy performance, reduced impacts and cost savings.

- While better, more standardized controls will reduce the need for installer and operator training, it is likely they will increase the need for training of service technicians. The lack of qualified personnel must be addressed by developing aggressive parallel training and credential packages.

**Getting Started**

We propose that an entity with the stature of the California Energy Commission or the US Department of Energy sponsor a *Building Controls Summit* to discuss these issues, better define specific problems and identify viable paths forward and the resources needed to pursue them. Government leadership is needed both to review regulatory options that could enhance energy performance and to kick-start the “skunk works” concept. Given the substantial private sector and utility interest in the development of the solution set, we believe that this topic would mobilize significant support.

**Summary**

The focus on buildings up until now has been, like the focus of the automotive industry of four decades ago, primarily on style, functionality and reliability with minor regard for energy performance or environmental impacts. For a number of reasons discussed above, controls have lagged behind other building systems, creating a patchwork of incompatible, proprietary approaches. But just as automobile manufacturers had to quickly develop effective engine controls to enable higher efficiency vehicles to meet regulatory demands while still remaining competitive in the marketplace, so can controls designers develop effective building solutions which reduce greenhouse gas emissions, energy use and environmental degradation.

We are facing a challenge and an opportunity in which the cost effectiveness of controls at both the building and societal levels is unquestioned. Where controls solutions can reduce and/or reverse environmental impacts threatening our way of life. The controls industry must evolve quickly to generate more energy savings from today’s buildings and enable much better levels of performance from the coming generation of high-performance buildings.
Interviewees for Controls White Paper

Paul Erlich, Building Intelligence Group
Tom Hartman, The Hartman Company
Philip Haves, Lawrence Berkeley National Laboratory
Mark Hydeman, Taylor Engineering
Michael Ivanovitch, Consulting Specifying Engineer
Curt Klaassen, National Building Controls Information Program/Iowa Energy Center
Bill Koran, Quantum Energy Services (formerly with PECI)
Jay Santos, Facility Dynamics
Steve Tom, Automated Logic Corporation
Dennis Wilde, Gerding/Edlen Development Group