Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential

Final Report

Prepared by

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BUILDING TECHNOLOGIES PROGRAM

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List of Abbreviations and Acronyms

The following list defines many of the more commonly used abbreviations and acronyms relevant to building systems used in this report.

AEC	Annual Energy Consumption
AFDD	Automated Fault Detection and Diagnostics
AHU	Air Handling Unit
AI	Artificial Intelligence
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BACnet	Building Automation and Control Networks
BCS	Building Control Systems
CABA	Continental Automated Buildings Association
CAV	Constant Air Volume
CBECS	Commercial Building Energy Consumption Survey
CCTV	Closed Circuit TV CCTV
DALI	Digital Addressable Lighting Interface
DCV	Demand Controlled Ventilation
DDC	Direct Digital Control
DOE	U.S. Department of Energy
EIS	Energy Information System
EMCS	Energy Management and Control System
ESCO	Energy Service Companies
FCU	Fan Coil Unit
FDD	Fault Detection and Diagnostics
FSM	Finite State Machine (control)
HTTP	HyperText Transfer Protocol
IAQ	Indoor Air Quality
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
LRC	Lighting Research Center
NILM	Non-Invasive Load Monitoring
OA	Outdoor Air
OEM	Original Equipment Manufacturer
OWBCS	Optimal Whole Building Control Systems
PECI	Portland Energy Conservation, Inc.
PID	Proportional-Integral-Derivative (control)
PIR	Passive Infrared (sensors for occupancy sensing)
PLC	Power Line Carrier
PNNL	Pacific Northwest National Laboratory
RTD	Resistance Temperature Detector
RTU	Packaged Rooftop Unit
SOAP	Simple Object Access Protocol

SPP	Simple Payback Period
UPnP	Universal Plug ‘n Play
VAV	Variable Air Volume
XML	eXtensible Markup Language
WBD	Whole Building Diagnostics

2 Executive Summary

Commercial buildings in the U.S. have more than 67-billion ft^2 of floor space and consume about 17 quads of primary energy per year, or about 17% of all U.S. energy consumption. TIAX carried out a study for the U.S. Department of Energy, Office of Building Technology (DOE/BT) to evaluate the energy saving potential of controls and diagnostics for commercial buildings through improved operation of energy-consuming building systems such as HVAC, lighting, and larger refrigeration systems. In the context of this study, *controls* are the hardware and software used to control indoor conditions to provide a safe, comfortable and productive environment for the building occupants. *Diagnostics* use measurements of building systems and equipment to evaluate their functionality and detect sub par performance, i.e., by comparing expected performance to actual performance. Both controls and diagnostics can operate at the central, system, equipment, or room level.

Almost all commercial buildings have at least very basic on-off control functionality to provide lighting, e.g., lamp fixtures controlled by light switches or a circuit breaker, and heating, e.g., a furnace controlled by a thermostat. In addition, many commercial buildings have time-based controls to turn on and off lighting and vary space conditioning at specified times of day, particularly when buildings are unoccupied. Over the past 25 years, direct digital controls (DDC) using software-based controllers have come to market, driven by dramatic increases in computing power and the concurrent miniaturization and cost decrease of computing power. This has greatly increased the flexibility and potential sophistication of building controls while decreasing their implementation cost, a trend that continues with current movement toward control communications over enterprise networks.

The combination of greater sophistication and lower cost has the potential to make a wide range of energy-saving controls approaches, including automated diagnostics, economically viable. Controls and diagnostics have the potential to realize large reduction in the approximately 17 quads of primary energy consumed each year by commercial buildings. Studies indicate that several more sophisticated controls approaches that consider a wider range of variables or automate control functions have significant national energy savings potential. On the other hand, greater complexity also appears to have increased the potential for faulty operation of building systems. An extensive quantity of evidence from case studies indicates that building systems often do not operate as intended and suffer from *faults*, i.e., deviations from intended or as-designed building equipment and systems performance that compromise their operational efficiency and waste significant quantities of energy. Consequently, diagnostics approaches also appear to have a significant national energy savings potential. An estimate of the national energy impact of specific faults does not exist, however, which impedes assessment of the national energy savings potential of specific diagnostic approaches.

Despite increases in functionality, reductions in cost, and evidence indicating the potential for substantial energy savings, more sophisticated building controls and diagnostics have had limited success in penetrating the $3 billion (per year) U.S. building controls market.

For example, centralized energy management and control systems (EMCS) serve only about 10% of commercial buildings (33% of floor space), while occupancy sensors for lighting control serve well under 10% of all commercial building floor space. The *global* market for indoor air quality sensors (including CO_2) did not exceed ten million dollars in 2001. Diagnostics, including building commissioning and even basic diagnostics such as comparative benchmarking of annual building energy consumption, have a very limited market share.

In sum, diagnostics and sophisticated controls have realized only a small portion of their energy-savings potential due to general market and control and diagnostic approach-specific barriers. This study took a four-pronged approach to understand the energy-saving potential of building controls and diagnostics and why they have had a limited impact upon the energy efficiency of the commercial building stock:

1. *Evaluate the Energy Impact of Faults*: Quantification of the national energy impact of specific faults;
2. *Assess the Energy Saving Potential of Control and Diagnostic Approaches*: Quantification of the national energy saving potential of specific control and diagnostic approaches;
3. *Analyze Barriers to Controls and Diagnostics*: Identification of general barriers that adversely impact the market penetration of all controls and diagnostics approaches, e.g., due to ownership and construction paradigms, and approach-specific barriers, and
4. *Analyze Drivers for Controls and Diagnostics*: Assessment of general drivers, such as enhancing the indoor environment, and approach-specific non-energy benefits that can enhance the adoption of controls and diagnostics in the market.

The key findings of this report are summarized in the four following sections that correspond to the four categories described.

2.1 The Energy Impact of Faults

TIAX carried out a literature review to identify problems that arise in building HVAC, lighting, water heating, and refrigeration systems and may increase building energy consumption. This uncovered more than 100 faults that occur in commercial building HVAC, lighting, and water heating systems. TIAX developed preliminary annual energy consumption (AEC) impact estimates for each fault and used these estimates to identify thirteen faults for further evaluation (see Table 2-1). For each fault selected, the project team assessed the quantity of commercial building energy consumption potentially impacted by the fault, how often the fault occurs such that it causes an appreciable increase in primary AEC, and the average percent increase in energy consumption due to the fault. The product of these three factors equals the fault's AEC.

Overall, the faults studied increase commercial building primary energy consumption by approximately one quad, or about 11% of energy consumed by HVAC, lighting, and larger refrigeration systems[1] in commercial buildings. Three faults, “HVAC Left on When Space Unoccupied,” “Lights Left on When Space Unoccupied,” and “Duct Leakage,” appear to account for about two-thirds of the total energy impact of the key faults (see Table 2-1).

Table 2-1: The AEC Impact of Faults Selected for Evaluation

Fault	AEC [quads[2]]
Duct Leakage	0.30
HVAC Left on When Space Unoccupied	0.20
Lights Left on When Space Unoccupied	0.18
Airflow Not Balanced	0.070
Improper Refrigerant Charge	0.070
Dampers not Working Properly	0.055
Insufficient Evaporator Airflow	0.035
Improper Controls Setup / Commissioning	0.023
Control Component Failure or Degradation	0.023
Software Programming Errors	0.012
Improper Controls Hardware Installation	0.010
Air-Cooled Condenser Fouling	0.008
Valve Leakage	0.007
TOTAL	1.0

The estimated likely range of the energy impact is quite broad, i.e., between 0.34 and 1.8 quads. Placed in the context of commercial buildings, the faults account for between 2% and 11% of all energy consumed by commercial buildings. Considering only systems primarily affected by the faults, that is, HVAC, lighting, and large refrigeration system energy consumption, fault-related energy waste equals between 4% and 20% of the energy consumed by those end uses. This range is broadly consistent with the 5% to 20% energy savings potential range reported in the retrocommissioning literature.

Most of the fault energy impact estimates have a high degree of uncertainty, most notably for controls-related faults for central HVAC systems. In no case do the data support a detailed analysis of fault energy consumption based on segmentation by building type and geographic region (e.g., CBECS). Several issues often arose often with the data sources (typically the building commissioning literature) that increased the uncertainty in fault energy impact estimates, including: inconsistent reporting of faults between studies and inconsistent data formats or level of detail, a tendency for commissioning studies to focus on problem buildings, and a concentration of commissioning studies in certain parts of the country.

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[1] Larger refrigeration systems include supermarket refrigeration systems and walk-in system.

[2] One quad equals a quadrillion, i.e., 10^{15}, btus. All energy data shown in the table are primary energy data, that is, taking into account the energy consumed at the electric plant to generate electricity.

This study provides several insights about building faults. First, it provides a bottom-up estimate for the overall magnitude of building faults, i.e., 0.34 to 1.8 quads. Second, it identifies the faults that likely have the greatest national energy impact. Third, it clarifies the specific type(s) of faults that have the largest impact within each broader fault type, including primary root causes for specific faults in several cases. Together, this information helps to prioritize diagnostic development efforts. Fourth, it points out the data required to improve the fault energy impact estimates for each fault. When combined with the national fault energy impact estimates, this information enables prioritization of future data gathering to focus on faults where the data will prove most useful.

The data to address the aforementioned gaps likely exist, but not in the public literature. Energy Service Companies (ESCOs) and utilities may have collected proprietary information to understand the cost-benefit relationship of different energy saving measures, including maintenance and commissioning. It is not clear, however, that this information would substantially alter diagnostic development priorities.

2.2 Energy Saving Potential of Control and Diagnostic Approaches

Diagnostics and more sophisticated controls have the potential to achieve substantial reductions in commercial building energy consumption. As illustrated in Figure 2-1, diagnostics provide the opportunity to reduce energy consumption by eliminating the gap between sub par system performance and as-intended performance, i.e., the energy impact of faults discussed in Section 2.1. Of course, non-diagnostic measures, such as improved maintenance practices or closer attention to operations, could also achieve some of the same energy savings as diagnostics. More sophisticated controls, on the other hand, enable additional savings above and beyond as-intended performance of building systems.

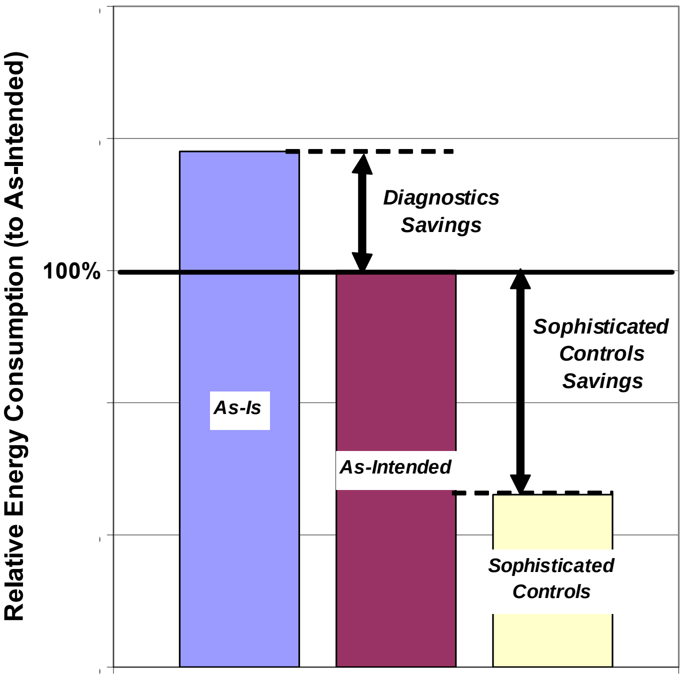

Figure 2-1: Illustration of Energy Savings from Diagnostics and Sophisticated Controls (*Note: Not To Scale*)

In conjunction with DOE/BT, TIAX selected a total of nine controls and diagnostics approaches and one group of enabling technologies (HVAC sensors) for evaluation based on an initial assessment of market-achievable energy savings potential. Other approaches not explicitly discussed in this report may also have significant energy savings potential, such as variable-speed drives and EMCS. For each approach, the team analyzed its:

- Background (what the option is, how it functions in buildings, how it saves energy, commercialization status);
- Performance Benefits (non-energy benefits of approach);
- Energy Savings Potential;
- Cost (economic assessment of approach);
- Barriers to Commercialization, and
- Technology Development "Next Steps" (to commercialize or increase market share).

Table 2-2 summarizes the technical energy savings potential[3] ranges for nine of the approaches; HVAC sensors do not directly save energy but are a crucial component of many controls and diagnostics approaches. Each approach is also characterized by its maturity stage:

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[3] Technical energy savings potential equals the annual energy savings if the technology were applied to the entire installed base of relevant equipment and systems.

- *Current:* Technologies that are currently in use but have not achieved broad market penetration;
- *New:* Technologies that are commercially-available but presently not used in commercial building HVAC equipment and systems;
- *Advanced:* Technologies yet to be commercialized or demonstrated and which require research and development.

The analysis found that more sophisticated controls have a higher national technical energy savings potential than diagnostics (see Table 2-2).

Table 2-2: Control and Diagnostic Approaches Evaluated

Approach		Technology Status	Relevant Energy Consumption [quad]	Technical Energy Saving Potential [quad]
Diagnostics	Commissioning	Current / New	9.2	0.5 – 1.8#
	Damper Automated Fault Detection and Diagnostics (AFDD)	Current / New	0.85	0.02 – 0.1
	Duct Leakage FDD	Advanced	3.1	0.15 – 0.4
	Packaged Rooftop Unit AFDD	Advanced	0.74	0.025 – 0.14
	Whole Building Energy AFDD	Current / Advanced	9.2	0.5 – 1.8*
Controls	Demand Controlled Ventilation (DCV)	Current	2.7	0.3
	Occupancy Sensor-Based Lighting Control	Current	4.2	0.6 – 2.3**
	Optimal Whole Building Control	Current / Advanced	9.2	0.5 – 1.3***
	Photosensor-Based Lighting Control	Current	4.2	0.4 – 0.8
Enabling	HVAC Sensors	Current / Advanced	4.5	N/A

#Commissioning may save all fault-related energy consumption, except possibly duct leakage.
*Saving from "Commissioning" represents an upper bound for both ends of the range.
**Could also eliminate unintentional "Lights Left on When Space Unoccupied," saving 0.02 to 0.13 quads.
***Includes energy saved from elimination of unintentional "Lights and HVAC Left On When Unoccupied."

It is important to note that the energy saving potentials of different approaches may not be additive, as savings realized by an approach can, to varying degrees, decrease and/or preclude energy savings achievable by other approaches. Nonetheless, a combination of selected controls and diagnostics approaches from Table 2-2 could reduce commercial building energy consumption by between 2.3 quads and 6.5 quads per year. In addition, the energy saving potential from space-specific lighting control strategies, i.e., occupancy and photosensors, have very high energy saving potentials.

Figure 2-2 presents average energy saving potentials and approximate simple payback period (SPP) ranges for the controls and diagnostics approaches evaluated, excepting photosensor-based lighting control (for continuous dimming systems, the SPP typically exceeds 10 years). The SPP ranges reflect average utility prices. Approaches that reduce outdoor air intake, improve cooling and ventilation equipment and system performance, and manage peak demand further decrease payback periods in areas with higher demand charges. The cost of implementing diagnostics dominates their SPP, with the notable exception of retrofit duct leakage FDD, where the cost of fixing the fault (i.e., duct sealing) dominates the cost.

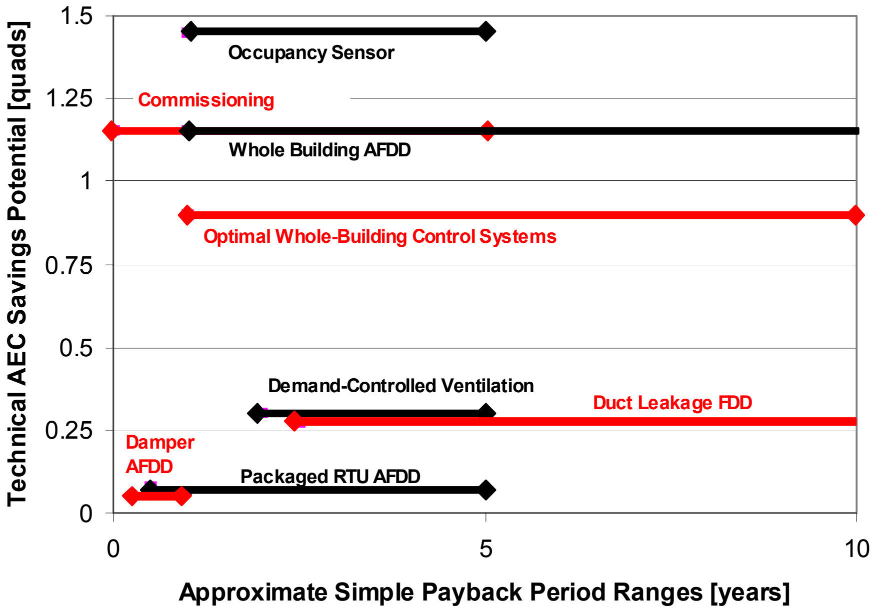

Figure 2-2: Estimated Technical Energy Savings Potential and Simple Payback Periods for the Nine Options

In addition, although factory-installed[4] equipment-specific diagnostics (such as packaged RTU and damper AFDD[5]) have much lower energy saving potentials than centralized approaches, they appear to offer attractive SPPs.

Most of the approaches have broad SPP ranges that depend upon the specifics of a potential application. For example, the SPP of centralized control or diagnostics approaches tends to be sensitive to the floor space impacted by the approach because relatively fixed costs account for a significant portion of system installed cost. Thus, for example, commissioning, optimal whole building control systems, and whole building AFDD will have significantly more attractive economics for larger buildings (e.g., several hundred thousand square feet) than smaller buildings. In many cases, this limits the market-achievable energy savings of these approaches, as buildings with less than 50,000ft^2 account

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[4] Retrofit packaged RTU AFDD and damper AFDD appears to have significantly longer payback periods due to the need for site-installed communications infrastructure and sensors; see Sections 9.2 and 9.8 for details.

[5] Language incorporated into ASHRAE Standard 90.1 has led to a very high prevalence of economizers in RTUs. Consequently, the energy impact of the dampers not working fault and the energy saved by damper AFDD will likely be significantly higher than the values shown in Table 2-1, Table 2-2, and Figure 2-1 (which reflects economizer market penetration in 1995).

for almost half of commercial building energy consumption. Analogously, room-level controls, such as occupancy sensors and photosensors for lighting control, tend to have shorter payback periods when they serve larger spaces and influence a larger quantity of energy consumption.

Overall, some common themes arise as to how the nine approaches reduce energy consumption (see Table 2-8).

Table 2-3: Common Themes to Energy Consumption Reduction

Energy Consumption Reduction Theme	Relevant Technologies
Automate Control Functions	• Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control
Eliminate Unnecessary Lighting	• Commissioning • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control • Automated Whole-Building Diagnostics
Eliminate Unnecessary Heating, Cooling and Ventilation	• Commissioning • Automated Whole-Building Diagnostics
Fault Detection and Diagnostics	• Commissioning • Dampers AFDD • Packaged RTU AFDD • Automated Whole Building Diagnostics
Reduce Excessive Outdoor Air Intake	• Commissioning • Dampers AFDD • Demand Controlled Ventilation • Duct Leakage Diagnostics • Automated Whole-Building Diagnostics

Recently, the concept of integrated building systems, i.e., systems that share information, has received considerable attention. It is not clear, however, that integrating building systems offers appreciable additional energy savings potential beyond the approaches described above. On the other hand, it may offer the possibility of increasing the *market-achievable* energy savings because sharing communications infrastructure can reduce the installed cost building controls while also providing additional value to building operators.

2.3 Barriers to Controls and Diagnostics

To varying degrees, all controls and diagnostics options face real or perceived economic barriers to entering the market. These include general barriers to energy efficiency measures, barriers specific to controls and diagnostics, and approach-specific barriers.

A central issue for all energy savings measures is that energy costs represent only a small portion of overall expenditures for most buildings, e.g., about 1% of *total* annual expenditures for an office building. Consequently, most building owners and tenants place a low priority on reducing energy expenditures. For buildings that will be let, the ultimate goal remains realizing the highest rate of return possible. Building owners are, therefore, keenly interested in having their property perceived as providing productive environments or generating superior images. Owners, however, have little incentive to increase energy efficiency because tenants usually pay for energy and typically care little about energy expenses.

Energy expenses may equal a higher percentage of operating expenses in retail or food sales buildings. In these cases, energy efficiency measures compete directly for funds that could be invested in core business functions, such as enhanced lighting or displays that increase sales. Consequently, building owners won't find building controls investments attractive without solid evidence of a quick payback period. Building owners and design professionals often believe that novel building controls carry greater financial risk than conventional controls, in large part due to insufficient examples and credible documentation of the costs, benefits, and operational experiences with different approaches. Developing rigorous and credible cost-benefit information for novel building controls is vital for these systems to gain building owner confidence and achieve significant market penetration.

The dominant new construction process paradigms for commercial buildings also tend to impede the effective deployment of more sophisticated controls and diagnostics. The most common paradigm, design/build, centers on a contractor selected by the owner to design and then construct the building. Design and construction occur largely independently and in sequence, which fixes many design variables early in the process to enable different parts of the construction processes to overlap. While this approach expedites construction, it often significantly constrains portions of the design decided later in the process. Much design work relies on formulas and rules-of-thumb and makes frequent re-use of elements from building to building. Often, building controls are not considered until late in the construction process, when funds are scarce and most of the building infrastructure has already been specified. Consequently, low-cost systems are "shoe-horned" into the existing infrastructure, creating a sub-optimal installation. Furthermore, the contractor who installs the controls often is not the same party who specified the controls, which also decreases the efficacy of controls. Recent modifications to the organization of the building construction process to include specific sections for communications and integrated automation in the MasterFormat^{TM} specification could enhance the potential for the owner and contractor to consider and deploy more sophisticated controls approaches and integrate building systems.

In contrast, a collaborative construction approach takes a broad view, emphasizing an integrated evaluation of design options. This increases the potential for achieving energy efficiency, including the use of building controls and diagnostics. Because it requires extensive up-front design integration and continued information sharing throughout a project, the collaborative approach has a higher first cost and takes longer to construct than design/build and plan/design/build. Most building owners view these factors as potent negatives. Overcoming these shortcomings will require dramatic changes in current building practice. For buildings with integrated building systems, a new type of contractor, the systems integrator, may be needed to manage and ensure effective systems integration throughout the new construction process.

More sophisticated building controls and diagnostics also face general barriers to greater use, including the high cost of retrofitting controls in existing buildings and equipment, low levels of understanding by key decision makers, and interoperability challenges. Existing buildings accounts for about 75 to 80% of total building control expenditures. Retrofitting of more sophisticated controls and diagnostics often requires installing additional sensors and communications infrastructure (pulling new wires), which can be prohibitively expensive and also disruptive to the current occupants. This highlights the value of technologies that decrease the installed cost of building controls, such as wireless communications. These measures can also benefit new construction because system installation accounts for approximately 70% of the installed cost of controls in new buildings.

A relatively low level of understanding of building controls and diagnostics by decision makers further inhibits deployment of more sophisticated controls. Not only do knowledge gaps impede their consideration, these gaps also form a cascade of sub par decision-making that compromises the efficacy of installed controls and diagnostics. When controls and diagnostics cannot realize their promised cost savings, this increases the perceived risk of controls and diagnostics investments and the reluctance of people to invest in those technologies. The evolution of building controls from pneumatic to electronic and digital has exacerbated this knowledge gap, and it is not clear that the current structure of the buildings industry can support the wages demanded by a software-centric building controls industry.

The commercialization of open communications protocols, such as BACnet ™ and LonTalk®, in the 1990s promised to enable interoperability between products offered by different controls vendors. In theory, this would increase competition for the provision of hardware and services and provide access to a wider range of functionality while reducing the first and ongoing costs of building controls. In practice, true interoperability has remained elusive because adherence to standards and protocols that ensure interoperability among diverse systems has not generally existed for building controls.

Each specific controls and diagnostic approach faces specific barriers to attaining significant market share. Besides high first cost, a lack of proven track record represents the largest market barrier for several of the ten approaches, most notably for diagnostic approaches (see Table 2-4). Approach-specific barriers are discussed in greater detail in Section 9.

Table 2-4: Common Barriers Facing the Ten Controls and Diagnostics Approaches

Barrier	Relevant Technologies
Cost / Payback Uncertainty	• Wireless HVAC Sensors • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control
Difficult to Implement	• Commissioning (schedule issues) • Wireless HVAC Sensors (lack of guidance) • Photosensor-based Lighting Control (placement and calibration)
Higher First Cost ("current" technologies)	• Commissioning • Damper AFDD • Demand Controlled Ventilation (CO_2 sensor cost) • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control • Automated Whole Building Diagnostics
Lack of Industry Awareness	• Commissioning • Duct Leakage FDD (of prevalence of duct leakage) • Optimal Whole Building Control Systems
Reliability Concerns	• HVAC Sensors (CO_2, humidity / enthalpy) • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control
Unproven Performance	• Duct Leakage FDD • Wireless HVAC Sensors • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Packaged RTU AFDD • Photosensor-based Lighting Control • Automated Whole Building Diagnostics (more advanced approaches)

Finally, the first cost of centralized building controls and diagnostics inhibits their deployment in smaller buildings. Most centralized controls leverage an EMCS and the cost of the centralized portions of an EMCS do not scale linearly with square footage. This usually results in a higher installed cost (on a $\$/ft^2$ basis) for centralized measures in smaller buildings. In addition, smaller buildings tend to have fewer zones, require less sophisticated control, and may not reap the same energy and maintenance benefits from centralized control. Recently developed EMCS-like products offered by major building controls vendors targeting light commercial buildings that offer EMCS-like functionality and are designed for integration with and control of RTUs could improve the cost-effectiveness of more basic centralized controls and diagnostics in smaller buildings.

2.4 Key Opportunities for Greater Deployment of Building Controls and Diagnostics

Maintaining occupant comfort ranks as the foremost goal of buildings operations, both to create a more desirable working environment and increase tenant retention. The dominance of worker salaries in office building expenses – they account for approximately 80% of expenditures in a small office building – suggests that building controls and diagnostics investments that enhance worker productivity or increase sales, even by only 1% or 2%, are the most attractive investments. For instance, a 2% increase in the productivity of office building occupants has the same economic impact as eliminating *all* building operations and energy expenditures. In all cases, **building controls and diagnostics can greatly increase their value by enhancing the core business of the building – be it employee productivity or sales of goods and services**. All parties benefit from a more productive environment. The building occupants realize the aforementioned gains and the lessor can command more rent for his property.

Prior research suggests relationships between productivity and several variables related to controls, such as personal climate control and outdoor air ventilation levels. Although building tenants appear to highly value measures related to occupant comfort, the owner/operator must link tenant comfort to financial parameters such as productivity to make a convincing business case for substantial investments. From the perspective of building owners and operators, the link between most building attributes, let alone building controls, and occupant productivity is not sufficiently well understood and documented to make a convincing business case for substantial investment. The sheer magnitude of the potential value from increased employee productivity provides, however, the motivation for further research to understand and document the linkage of productivity to lighting, environment control, indoor air quality (IAQ), etc. Similarly, building controls and diagnostics can also add value by preventing productivity degradation (e.g., from sick building syndrome) or lawsuits linked to poor IAQ (e.g., due to mold).

Reducing energy expenditures is another, more moderate value proposition for building controls and diagnostics. Although utility expenses account for only about 1% of total building expenses, they do account for about 30% of operating expenses. Actual savings depend on gas and electric costs, in particular, peak demand charges (that account for, on average, about 40% of commercial building electricity expenditures). Lighting and HVAC represent about 75% of commercial sector peak electricity demand and building controls have the potential to achieve substantial reductions of both end uses via peak-shaving functions, such as switching off portions of indoor lighting or allowing indoor temperature setpoints to rise during periods of notably high peak demand. Many EMCS have the capability to implement measures that limit peak demand, but only a relatively small percentage of building operators actually use this capability.

Building maintenance expenses account for more than 20% of office building operating expenses. Consequently, controls and diagnostics measures that offer cost-effective reductions in maintenance expenses can prove attractive. For example, centralized building controls can be sold – and EMCS were initially marketed– as a way to monitor building performance to reduce maintenance and operations expenses. In theory, reduced maintenance and operations costs decrease the payback period of an EMCS. In practice, the payback calculations often only consider energy savings because maintenance savings are difficult to quantify.

Several of the nine controls and diagnostics approaches offer one or more of the non-energy benefits discussed (see Table 2-5).

Table 2-5: Common Non-Energy Benefits of the Nine Controls and Diagnostics Approaches

Non-Energy Benefit	Relevant Technologies
Ensuring Adequate Outdoor Air Intake	• Commissioning • Damper AFDD • Demand-Controlled Ventilation
Improved Occupant Comfort	• Commissioning • Damper AFDD • Duct Leakage FDD • Packaged RTU AFDD • Automated Whole Building Diagnostics
Notable Peak Demand Reduction	• Commissioning • Damper AFDD • Demand-Controlled Ventilation • Duct Leakage FDD • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Packaged RTU AFDD • Photosensor-based Lighting Control (daylighting) • Automated Whole Building Diagnostics
Decreased Maintenance Costs	• Commissioning • Packaged RTU AFDD • Automated Whole Building Diagnostics

Finally, technologies that reduce the installed cost premium of building controls and diagnostics can improve their economic attractiveness. All of the ten options could be readily retrofit into existing equipment or buildings, which would allow them to penetrate the existing building stock much more rapidly than technologies limited primarily to new construction and major renovation. The cost of retrofitting many approaches, however, can be much higher than incorporating the approach in new construction or major renovations. For example, factory integration of additional sensors and microprocessor capabilities in existing equipment, such as for damper AFDD or RTU AFDD, would cost much less than retrofitting diagnostics into equipment. In the case of centralized systems, installation, including wiring and electrical work, accounts for more than half of the installed cost; indeed, installation and commissioning account for at least 70% of total installed cost. Consequently, greater deployment of measures that significantly reduce the cost of installing controls, such as structured/shared cabling systems for building systems and cost-effective wireless sensors and communications, can improve the economic attractiveness of several more sophisticated building controls and diagnostics approaches. Furthermore, the nascent practice using enterprise networks to also communicate controls-related information offers the potential to reduce cost by sharing communications infrastructure while also increasing functionality by facilitating information sharing between building and business systems. In the future, enterprise networks could also devolve some control of occupied space to building occupants by allowing input on space conditions, such as temperature. Greater personal control of the environment, in turn, tends to enhance occupant comfort.

Wireless sensors and communications products have begun to enter the buildings market. Ongoing efforts to develop low-cost and easy-to-implement wireless sensors and communications promise to improve the future economics of retrofitting controls and diagnostics in buildings, as well as to facilitate the devolution of control to individuals. Intriguingly, a major building controls manufacturer has begun offering a wireless solution that provides pervasive indoor wireless communications access via radio frequencies for several different applications, including building controls. It is conceivable that building owners might install this solution primarily to provide cell phone and Wi-Fi service in buildings and building control applications would leverage the wireless infrastructure. This would decrease the effective installed cost of measurement points for building control.

In addition, the use of low-cost and high-accuracy MEMS-based sensors in the HVAC industry will enhance the prospects for greater deployment of diagnostics in new equipment and buildings. MEMS-based humidity and CO_2 sensors that increase sensor accuracy and reduce sensor maintenance could also increase the effective use of enthalpy-based economizers and demand-controlled ventilation, respectively.

Owing to the different barriers and developmental stages of the nine controls and diagnostics approaches evaluated, future efforts to promote widespread application of these approaches range from research to market transformation (see Table 2-6). Section 9 details approach-specific "next steps."

Table 2-6: Technology Development Potential "Next Steps" for the Nine Controls and Diagnostics Approaches

Potential "Next Step"	Relevant Technologies
Research & Development	• Commissioning • Duct Leakage FDD • Optimal Whole Building Control Systems • Automated Whole Building Diagnostics
Education	• Commissioning • Demand Controlled Ventilation (clarification of ASHRAE Standard 62) • Duct Leakage FDD (problem of Duct Leakage) • Wireless HVAC Sensors • Photosensor-based Lighting Control
Demonstration and Evaluation	• Wireless HVAC Sensors and Controls • Optimal Whole Building Control Systems • Packaged RTU AFDD • Automated Whole Building Diagnostics
Market Promotion / Deployment	• Commissioning • Dampers AFDD • Occupancy Sensors • Packaged RTU AFDD

Overall, building controls and diagnostics have the potential to realize large reductions in commercial building energy consumption, both by eliminating sub par building operations and improving building system performance. More importantly, they can enhance the comfort of the indoor environment and the reliability of building operations, both of which may increase organizational productivity. Several favorable technological trends, notably lower-cost wireless communications, enterprise networks, sensors, and controllers, suggest that the cost of realizing these benefits will continue to decrease – and this reduction may even accelerate – in the future.

3 Introduction

Commercial buildings have long had basic building controls to regulate key buildings systems, including HVAC, lighting, refrigeration, and water-heating systems to create a comfortable and productive environment. Initially, building controls had basic on-off functionality that individuals manually actuated locally. For example, a boiler room operator turned on and off boilers in response to estimated building heating demand and building operations personnel would turn on and off lighting panels. Centralized building control systems first appeared in the 1960s that allowed remote operation of building systems. Initially, they appeared in only the largest new construction where the first cost of the system could be amortized over the entire building and realize reductions in buildings operation and maintenance staff. When energy became a significant concern in the 1970s due to the run-up in energy prices, centralized control of building systems through energy management and control systems (EMCS) with energy-saving functionality such as separate day and night schedules for HVAC and lighting, and demand control, increased.

These earlier central control systems used pneumatic communications and controls, i.e., control signals and measurements were communicated as pressure levels through long plastic tubing runs that snaked through buildings. Electronic and computer-based controllers relied upon pressure-to-current (P to I) converters for inputs and current-to-pressure (I to P) converters for outputs. As electronic and computing technology advanced, electronic control signals became prevalent. This includes the use of direct digital controls (DDC) for serial communication of data, e.g., from supervisory controllers to an EMCS. Over time, the dramatic increases in computing power and the concurrent miniaturization and cost decrease of computing power enabled software controllers to supplant hard-wired control logic. This greatly increased the flexibility and potential sophistication of building controls while decreasing their implementation cost, a trend that continues with current movement toward control communications over enterprise networks.

The combination of greater sophistication and lower cost has the potential to make a wide range of energy-saving controls approaches, including automated diagnostics, economically viable. Controls and diagnostics have the potential to realize large reduction in the approximately 17 quads of primary energy consumed each year by commercial buildings (see Figure 3-1). On the other hand, greater complexity appears also to have increased the potential for faulty operation of building systems.

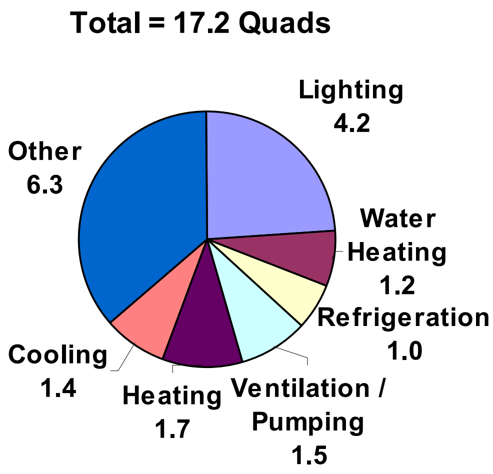

Figure 3-1 : Breakdown of U.S. Commercial Building Primary Energy Consumption circa 2002 by End Use (EIA 2003, Navigant Consulting 2002, ADL 2001a, ADL 1999, ADL 1996)

To understand the energy-saving potential of commercial building controls and diagnostics and support its strategic planning efforts, the U.S. Department of Energy, Building Technologies Program, contracted TIAX LLC to perform a study to assess:

1. *The Commercial Building Controls Market* – Focusing on key barriers to and strong value propositions for controls and diagnostics;
2. *The Energy Impact of Buildings Faults* – The energy wasted by building systems due to sub par operation;
3. *The Energy-Saving Potential of Controls and Diagnostics* – The energy-saving potential of specific controls and diagnostics approaches, and
4. *The Commercial Potential of Controls and Diagnostics Approaches* – The economics, key non-energy benefits, and key barriers to commercialization of greater deployment of specific approaches, including recommending “next steps” to overcome the key barriers.

This report contains the methodology, results, findings, and recommendations of the study, organized as follows:

Section 4, “Commercial Building Controls,” provides a basic overview of control strategies, diagnostics approaches, communications for controls, and energy management and control systems (EMCS). A related appendix (Appendix A) contains additional information about control components

Section 5, “The Building Controls Market and How It Influences Building Controls Investments,” discusses how the structure of the current building controls market, different building management paradigms, and construction paradigms affect controls investments.

Section 6, “Barriers to Building Control Systems and Diagnostics,” describes key barriers exist to the deployment of building controls, particularly more sophisticated controls.

Section 7, ”Drivers for Building Control Systems and Diagnostics,” pinpoints desirable characteristics of building controls that can enhance their market attractiveness.

Section 8, “The National Energy Impact of Building Equipment and System Faults,” identifies key faults, analyzes their national energy impact, and points out data gaps that increase the uncertainty of the energy impact estimates.

Section 9, “Assessment of Controls and Diagnostics Approaches,” evaluates the technical energy saving potential, economics, non-energy benefits, and barriers to commercialization or greater deployment of ten specific controls and diagnostics approaches. It also presents recommended developmental “next steps” to enhance the market-achievable energy saving potential of each approach.

Section 10, “Summary, Conclusions and Recommendations,” summarizes the key findings of the study.

4 Commercial Building Controls

Building owners install building controls to provide a safe, comfortable and productive environment for the building occupants. In the context of this report, building controls refers to the control of building systems that have a major impact on overall building energy consumption, namely HVAC, lighting, larger refrigeration, and water-heating systems and equipment. Building controls can be further sub-divided by functionality into several different classifications (see Table 4-1).

Table 4-1: Building Control System Functionality Classifications (based on Lowry 2002)

Building Control Functionality Classification	Examples
Plant Control	Space temperature control, boiler sequencing
Plant Maintenance	Fault reporting/alarming, filter conditioning monitoring, equipment "run-time" monitoring
Energy Saving	HVAC/lighting scheduling, demand limitation, building night purge
Recording	Energy metering, energy use monitoring (e.g., gas, electric, oil)

Building controls can control at either the central (i.e., energy management and control systems, or EMCS) or equipment/system level. Centralized building controls, particularly as part of an EMCS, can perform a wide range of different building functions. Currently, although EMCS serve only about 30% of commercial building floor space, most commercial buildings of *all* sizes likely have some degree of the basic control functionality found in an EMCS. For example, about 80% of commercial buildings vary their building temperature setpoints for heating and cooling during unoccupied periods (EIA 1999).

There are several building equipment categories in addition to HVAC and lighting that may have control systems (see Table 4-2). More advanced building controls may leverage functionality (e.g., sensing) from other building systems to enhance building control functionality or share infrastructure to reduce cost.

Table 4-2: Common Building Systems (based on BOMA 2000)

Building Systems	Functionality
Access Control	Building access systems, e.g. key cards
Fire / Life Safety	Fire detection and alarming, fire response, fire suppression
HVAC	Climate control (temperature, humidity), ventilation
Lighting	Lighting control
Security	Building alarm monitoring, surveillance cameras (Closed-Circuit TV a.k.a. CCTV)
Vertical Transport	Elevator and escalator control

This section strives to provide the non-expert reader with a basic understanding of control strategies, diagnostics approaches, communications for controls, and energy management and control systems (EMCS). Appendix A contains additional information about control components (i.e., Sensors, controlled devices (e.g., valves, dampers), controllers, thermostats), as well as commercial building systems and equipment and how they are controlled. Together, this material provides the basis to understand how specific faults increase energy consumption and specific control approaches reduce energy consumption.

4.1 Control Strategies and Algorithms

Control systems attempt to keep a controlled variable within an acceptable performance range so that a piece of equipment or a system can achieve its desired functions. For example, a packaged rooftop unit (RTU) control system maintains comfort in conditioned spaces by controlling the levels of temperature, humidity, and ventilation levels. Automatic controls turn on and off, modulate, stage or sequence mechanical and electrical equipment to meet heating, cooling, and ventilation loads using pneumatic, mechanical, electrical, and/or digital control devices that respond to sensed control variables or time-of-day.

The majority of automatic control systems use closed (or feedback) loop control. Figure 4-1 depicts a block diagram for a very simple HVAC system control loop.

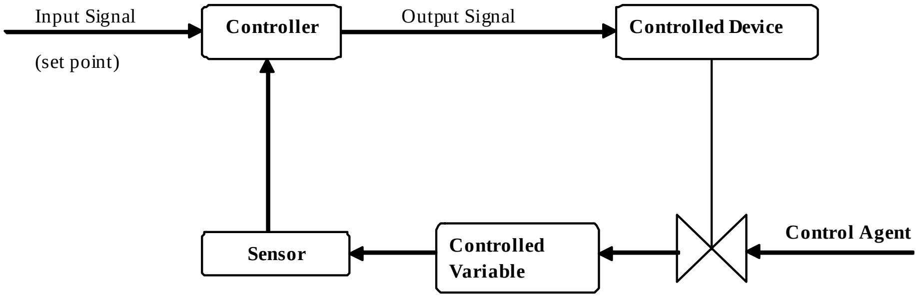

Figure 4-1: Schematic of a Basic HVAC Control Loop (based on ASHRAE 2001)

The *sensor* measures the *controlled variable* and sends a signal (pneumatic, electric or electronic) having a pressure, voltage or current value proportional to the value of the measured variable to the *controller*. The controller compares this value with the *set point*, i.e., the desired value of the controlled variable, and transmits a signal to the *controlled device* for corrective action. The controlled device receives the signal from the controller and reacts to vary the *control agent*. The control agent effects a change in the controlled variable and the process starts again when the sensor measures the controlled variable, completing the loop.

Thermostat-based temperature control of a home furnace is a common example of a closed loop control application depicted in Figure 4-1. A digital thermostat is a thermal switch (controller) with an embedded temperature sensor that measures the air temperature (controlled variable). The sensor sends a signal representing the temperature measurement to the thermostat controller. The controller compares this value to the temperature set point (input signal) and then sends an on-off (output) signal to the furnace (controlled device) to tell it to fire or not. The furnace heats the air and the hot air (control agent[6]) flows to the house to meet the heating load.

4.1.1 Types of Control Actions

A controller modifies the controlled device when it senses a deviation of the controlled variable from its set point. Hardware and software controllers can both be classified according to the following most common types of control action.

Two-Position (On-Off) Action

In simple two-position system control, the actuator has only two fixed positions, usually on and off. Figure 4-2 illustrates an example of two-position control in a home heating system.

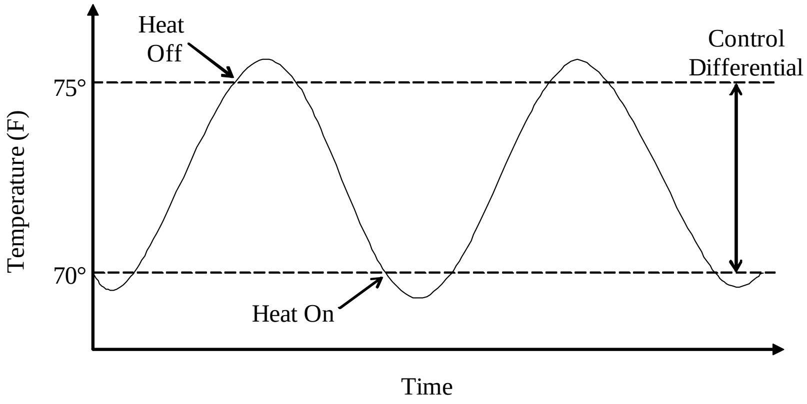

Figure 4-2: Two-Position Control (based on ASHRAE 2001)

In two-position control action, the control differential equals the difference in the controlled variable that occurs between the two positions. In Figure 4-2, the thermostat calls for heating when the zone temperature falls below the set point of 70°F and turns off the heat when the zone temperature rises to 75°F, i.e., the control differential equals 5°F. Commercial control systems extensively use two-position control because of its simplicity and low cost. Two approaches used to alleviate the overshoot that often occurs with two-position control action are anticipation and timed two-position action. Anticipation applied to two-position action uses heat anticipation[7] to reduce overshoot of the space temperature. Timed two-position control with anticipation action turns on the heating or cooling element for a time interval proportional to the temperature deviation from the set point.

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[6] Common control agents include: air, steam, gas, water, and electric current.

[7] A thermostat with anticipation action energizes a heating element during “on” periods which warms up the thermostat. This causes the thermostat to reach its setpoint before the room air (anticipating the rise in room air temperature) and shortens the “on” time.

Floating Action

In floating action, the controller moves the controlled device toward either its open or closed position, usually at a constant rate. Most controllers have a "dead band" between the two positions in which the controlled device may stop at any position when the controlled variable lies within the (controlled variable) dead band of the controller. Figure 4-3 illustrates floating control action.

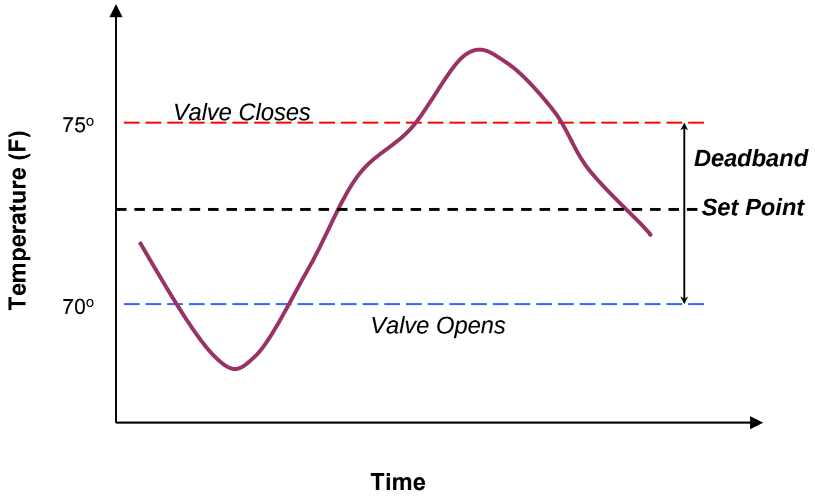

Figure 4-3: Floating Control (ASHRAE 2001)

In Figure 4-3, the controlled variable is the temperature, the set point is 72.5°F, and the dead band equals 2.5°F on each side of the set point. When the temperature moves outside the dead band, the controller moves the controlled device in the proper direction, either more closed or more open in the case of a valve. In order for floating control to function properly, the controlled variable must respond relatively rapidly to the controller signal. Similarly, the sensor and the controller both must have significantly shorter time constants than the controlled system to ensure reliable control of the system.

Modulating Control

Modulating control varies the output of the controller continuously over its entire output range. The *throttling range* denotes the amount of change in the controlled variable required to cause the controller to move the controlled device from one end of its stroke to the other. The controller *offset* (also called drift, deviation, or error) equals the difference between the set point and the actual value of the controlled variable.

Three typical modulating control actions are *proportional* action, *proportional plus integral* (PI) action, and *proportional-integral-derivative* (PID) action. In proportional control action, the output of the controller is proportional to the difference between the controlled variable and its set point. The proportional gain is usually an adjustable quantity. High gain makes the system more responsive but may make the system unstable. Conversely, lowering the gain decreases responsiveness but increases system stability. Proportional control will always result in some offset (i.e., difference between the set point and the controlled variable), which usually adversely affects system performance, occupant comfort and system energy consumption. However, due to the simplicity of this type of control action, most pneumatic and older electrical HVAC control systems employ proportional action.

PI action improves on simple proportional control by integrating the offset over time. This eliminates the offset typical of proportional action and increases system stability, improving control accuracy. Most electronic HVAC controllers and many HVAC pneumatic controllers employ PI control action. PI control action, however, does not perform well with dynamic set points, where sudden load changes occur or if the throttling range is small.

PID action includes the time rate of change of controller error, i.e., its derivative, in the control process, adding anticipatory action to the controller. This provides faster response and can improve loop stability. However, it also makes the controller more sensitive to noisy signals and harder to tune than a PI action controller. Most HVAC systems respond relatively slowly to changes in controller output, in which case PID action may over control, i.e., unnecessarily controlling the variable during a system-induced lag in response. In that case, the anticipatory action of the derivative term adds limited value. Overall, although many electronic controllers are available with PID action, the extra derivative feature often does not improve HVAC control (ASHRAE 2001; Sellers 2003b).

The ability to apply sophisticated controls does not necessarily mean that those controls are the most appropriate decision for all control loops. For example, application of PID control can lead to dramatic (~ten-fold) increases in commissioning and tuning, as well as operations and maintenance costs (Sellers 2003a). Sellers (2003b) discusses criteria for determining which components of HVAC systems to control using PID.

Finite state machine (FSM) controls can use different control algorithms for different operating regimes (states) delineated by key variables. The FSM control system enables control loop tuning within each specific state, resulting in superior control for each state relative to a single control algorithm, e.g., more aggressive tuning. It may also limit the controller response time to prevent oscillation between operating states. In one instance, an air-handling unit used FSM control to implement different algorithms for four different states delineated by the outdoor air condition: heating, economizing, cooling plus economizing, and cooling (Seem et al. 1999). In this case, the FSM control system used three separate PI controllers, one each for the heating coil, cooling coil and dampers.

Equal margin performance-based control is an emerging approach to controlling systems with variable-speed components, notably chiller plants (including the chiller, chilled water distribution system, and cooling tower) operated with variable air-volume ventilation systems. Applied to both system design and operation, it minimizes overall system energy consumption by operating all system components such that all have the same partial derivative of the overall system output (in heat flux) with respect to component power draw while still satifsying component or system requirements limitations (e.g., of supply air temperature for dehumidification). To determine the ideal operating point, the controller of the overall system increases or decreases the power to each component by a small increment, independently for each component, i.e., the input to only one component is modified at a time. Subsequently, the controller marginally reduces the power draw of the devices with smaller partial derivatives while marginally increasing the power draw of dives with higher partial derivatives. Overall system power draw decreases and, through iterative application of this process, reaches a minimum when the partial derivatives are equal. Applied to design, this same iterative approach can be used to select system components that enable effective and low-energy operation under a broad range of expected operating conditions (Hartman 2005a).

Artificial Intelligence-Based Control

Artificial Intelligence-based (AI) controls represent a different approach to controls than conventional P, PI and PID control loops. Instead of relying upon system models for control, AI controls consider system inputs and outputs and develop mathematical relationships (functions) between them to model the system. Krarti (2003) describes three different AI controls approaches for buildings: neural networks, fuzzy logic, and genetic algorithms.

Artificial neural networks attempt to mimic the human brain's problem-solving process. An artificial neural network "looks" at system data and uses statistical analysis to build a system of "connections" between different system variables (e.g., for HVAC, outdoor temperature, space temperatures, time of day, time of year, etc.) that model system behavior (e.g., building and building component energy consumption). In controls or diagnostics applications, a neural network attempts to find the most accurate relationship between variables by modifying the weights that describe the strength of connections (functional dependence) between those variables. Neural networks go through a training period during which the controller “learns” the strength, or weights, of different connections. The controlled system operates under a wide range of conditions and the controller observes how closely the actual system outputs match the predicted outputs. In response to the system outputs, the controller varies the weights of the connections in an attempt to minimize an error function. This process repeats until the measured error falls below a selected threshold. Neural networks tend to work best for problems without precise answers that are best solved via pattern recognition (Control Systems Unlimited 2003). At least one vendor sells an EMCS-based neural network tool for managing energy costs in real time (WebGen 2003).

Fuzzy control[8] establishes a set of “verbal” rules to control system operation instead of mathematical models of the system. Instead, the system consists of many rules that describe

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[8] Numerous sources exist for information about fuzzy control, e.g., http://www-2.cs.cmu.edu/Groups/AI/html/faqs/ai/fuzzy/part1/faq-doc-0.html .

smaller portions of the system and uses fuzzy logic to infer overall system control response and control actions. For example, fuzzy logic might state “If the temperature is cold, then increase the valve opening”. These rules are consistent with the way people talk about controlling systems, but they require interface to their input and output variables. The interface to input variables is called “fuzzification” and the interface to output variables is called “defuzzification.” An algorithm converts an input variable, such as temperature, into a series of functions that describe the degree that variable correlates with a set of values such as {cold, cool, comfortable, warm, hot}. Fuzzy logic theory determines the appropriate output for the given set of control rules. The change in the valve setting may have fuzzy values such as {very negative, slightly negative, zero, positive, very positive}. Application of the control rules assigns a degree of suitability to each of these possible actions. The “defuzzification” process then converts the fuzzy values into an appropriate change in the output value, for instance in the position of the valve. Fuzzy control is appropriate for situations where qualitative information may provide more insight that quantitative information. Very few building controls appear to use fuzzy logic (ADL 2002).

Simple forms of adaptive control incorporate classical PID control, with the capability for real-time adjustment (tuning) of the control coefficients based on system behavior. More complex approaches can involve other strategies to improve control, such as the following:

- Adjusting control based on predicting system input parameters, such as weather forecasts, that impact future HVAC needs
- Responding to inputs from users or system dynamics to learn desired operating patterns.

Genetic algorithms attempt to mimic natural selection to arrive at the “fittest”, i.e., most accurate, control algorithm. Initially, the controller creates a series of randomly generated models for predicting system outputs from the inputs. The controller then begins mutating (altering) portions of the algorithm and observes whether the accuracy of the output improves or not, i.e., it assess the fitness of the algorithm. The controller selects mutations that improve accuracy and keeps them for the next set of mutations; the controller discards less fit mutations. Mutation often begins randomly and then becomes progressively more probabilistic as algorithm accuracy improves. To date, genetic algorithms have had minimal application in actual HVAC systems.

4.2 Diagnostics

Diagnostics systems evaluate the functionality and performance of building equipment and systems. A type of diagnostics, prognostics, builds on diagnostic information about system performance to assess the likely lifetime of system components and develop maintenance recommendations (Brambley and Katipamula 2004). Friedman and Piette (2001) notes four basic diagnostic steps. First, the diagnostic system must acquire data that reflects building system or equipment performance (detection). Second, the system stores the data to keep a historical record of performance and pre-processes the data to make it more informative and facilitate diagnostics. Third, the system evaluates the data to detect potential problems. Fourth, the system analyzes data that suggest potential problems to develop a diagnosis.

Friedman and Piette (2001) categorize diagnostics as either manual or automated diagnostics (see Table 4-3).

Table 4-3: Characteristics of Manual and Automated Diagnostics

Diagnostic Type	Description
Manual	• Help extract information from raw data • Requires interpretation of data by knowledgeable operator to make diagnosis
Automated	• Software performs most reasoning (via Uses modeling, statistical analysis, etc.) for diagnosis

In general, as noted by Friedman and Piette (2001), the diagnostics deployed in current buildings have a much greater emphasis on monitoring and ensuring basic equipment functionality instead of detecting subpar performance or identifying ways to optimize operation. This almost certainly reflects the much higher priority that building owners place on maintaining occupant comfort than on reducing energy expenditures (see Section 7) and parallels the general focus of preventive maintenance tasks on ensuring functionality instead of improving operation (Gordon and Haasl 1996).

The following subsections discuss automated fault detection diagnostic (AFDD) analytical techniques in more detail and, subsequently, the application of diagnostics with EMCS and HVAC equipment.

4.2.1 Automated Fault Detection and Diagnostics Methods

An essential function of any AFDD system is to distinguish correct/normal operation from incorrect/abnormal operation. A wide range of analytical and computational techniques can be applied to automated functional testing[9] and diagnostics procedures used in commissioning, continuous commissioning, or AFDD. These analytical techniques fall into two categories, *first principles-based methods*, which incorporate models of building system performance, and *data driven methods* that primarily rely on experience with and knowledge about building system performance (Portland Energy Conservation Inc. 2003). Although most techniques contain elements of both of these general approaches, the distinction between primarily theoretical methods versus primarily empirical methods has implications for their applicability and efficacy to different applications. Table 4-4 provides an overview of the various analytical techniques, or methods.

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[9] Functional testing puts selected systems through a series of operational procedures and compares system behavior to the intended behavior to evaluate system performance. The tool uses the information to detect deviations from expected performance, i.e., faults, and then diagnose the fault's cause.

Table 4-4: Automated Fault Detection and Diagnostics Analytical Methods (based on Briggs 2001, PECI 2003)

Method Type	Methods	Description
First Principles-Based Methods	Engineering Calculation-Based	• Based on straightforward engineering calculations • Use mostly steady-state calculations similar to calculations used in design of systems
	Model[10] and Simulation-Based	• Computer programs that model, analyze, and predict thermal behavior and energy consumption characteristics of buildings and building systems, equipment, and compnents • Examples: *whole building*: EnergyPlus, DOE2, BLAST; component-level models
	Heuristic Rule-Based	• Rules of thumb developed by experienced individuals • Provide shortcuts and a more offer expedient way to meet analytical needs than more rigorous approaches (engineering calculation & simulation)
	Expert Systems	• Uses expert experience to create knowledge base of rules (more detailed knowledge than Heuristic Rule-Based, i.e., usually uses IF-THEN logic to infer state) • Expert system shells contain inference engines that determine if additional data are needed, then infers a diagnosis
	Fuzzy Logic	• Software algorithm that draws inferences based on fuzzy conditions • Addresses problems that cannot be easily solved using traditional (Boolean) logic
Data Driven Methods	Statistical Methods	• Pattern recognition methods that identifies patterns in the relationships between system inputs and outputs • Parametric: Uses both first principles-based knowledge and empirical data • Nonparametric: Based purely on empirical knowledge
	Artificial Neural Networks	• Analogous to neurobiological processes • Sets of interconnected nodes, which serve as computational centers that pass data back and forth between connected nodes. • Type of nonparametric statistical method

Much of the following discussion of these methods reflects information from Briggs (2001) and PECI (2003), while VTT (2001) discusses several methods in further detail.

4.2.1.1 First Principle-Based Methods

First principles-based methods are derived from building physics that govern the behavior of building energy systems. These methods analyze building thermal energy use behavior based on a well-established body of theory and practical engineering procedures. First

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[10] The authors added "Model" to the title of this method to make clear that this method applies to system-, equipment-, and component-level models as well as simulations.

principles-based methods are best applied to well-understood problems that have tools available for performance analysis. These methods define how the building system or equipment *should* perform and compare actual and theoretical performance to diagnose faults. Consequently, they offer the most direct method to confirm that design goals have been satisfied and inherently provide a benchmark for acceptable performance. Since these methods were developed for modeling building systems and equipment as they *should* perform, they often have difficulty modeling faulty performance. Building commissioning uses at least five types of first principles-based methods: engineering calculation-based methods, simulation-based methods, heuristic rule-based methods, expert systems, and fuzzy logic.

Engineering Calculation-Based Methods

These traditional commissioning methods are based on (primarily) steady-state calculations similar to those used by design engineers in the design of new systems. The methods are well developed, easy to implement in almost any software environment, and require only simple processing using conventional functions. They have been tested using manual commissioning procedures (PECI 2003). On the other hand, the steady-state methods are geared towards design and often have difficulty adjusting to actual, off-design conditions. An example of this approach is to calculate actual damper position using an energy balance based on air temperature and flow measurements to determine if outdoor air dampers operate as-intended. The accuracy of engineering calculation-based methods can be extended over a greater range of operating conditions by using more robust models for the relevant component and/or systems.

Simulation-Based Methods

Computer simulation tools have been used for over 30 years to model, analyze, and predict the thermal behavior and energy consumption characteristics of buildings, their systems, and building equipment. A few of the more popular simulation tools at the whole building level include EnergyPlus, DOE2, and BLAST. These tools yield estimates of many building and equipment operating parameters, such as peak and instantaneous power consumption, cumulative energy consumption, air flow rates, and zone temperatures. The power of simulation-based methods lies in their capability to accurately estimate building system performance under as-intended operating conditions. To achieve this accuracy, however, these tools require extensive inputs and are computationally intensive. For example, a building operator might compare actual building energy consumption to simulated building energy consumption under the same environmental conditions to detect excessive whole building energy consumption.

A researcher for a major global building controls manufacturer notes that the non-linear behavior of control components, such as actuators, complicates developing useful models of HVAC system behavior for diagnostic purposes. In addition, he implies that a sizeable portion of HVAC systems operate in an unstable fashion. This further complicates implementation of diagnostics, which may reflect models of steady-state system behavior (VTT 2001).

Heuristic Rule-Based Methods

Heuristic rules are rules of thumb that have been derived through experience and have proven operationally useful. Experienced individuals with an in-depth understanding of the operational domain typically develop the heuristic rules. The rules provide shortcuts and offer an expedient way to meet analytical needs in contrast to more rigorous – but costly and time-consuming – approaches (e.g., engineering calculations or simulations). Heuristic rules usually do not work well outside of their intended (design) domains and may lack robustness for more complex systems. For example, heuristics may work well for an isolated system or piece of equipment applied in different contexts, but a heuristic developed for a specific building would likely prove simplistic and unreliable in other buildings. Thus, heuristics should be used with caution in automated commissioning systems. An example of a heuristic might be: if the outdoor air temperature falls below 70^{o}F, the second chiller should be off.

Expert Systems

Expert systems use the experiences, knowledge, insights, and/or guidance of individuals with recognized expertise in the field. The knowledge of these experts is collected through interviews and entered into a database, referred to as a knowledge base, in the form of if-then statements. Haves and Khalsa (2000) provide an example of an expert system rule: *IF* the control valve is closed *AND* the supply fan is running *AND* the temperature rise across the heating coil is greater than the combined uncertainty of the sensor readings *THEN* the operation is faulty. Software packages employing expert systems are called expert system shells. These expert system shells contain a software component referred to as an inference engine, which infers additional information it needs to reach a conclusion or diagnosis based on the information entered by the user. After receiving the additional data, the inference engine infers a conclusion or diagnosis. Expert systems only work as well as the experts who create them, i.e., they are limited by the knowledge and insight of their creators. The use of expert systems in the building industry for fault detection and diagnosis has been exploratory, to date (PECI 2003). Existing knowledge bases have been used purely for demonstration purposes and their lack of availability is an impediment to the use of expert systems. It may be difficult to create an expert system with a high level of reliability, notably one that achieves a low incidence of false positives.

Fuzzy Logic

Fuzzy logic was developed by computer scientist to enable software programs to draw inferences based on uncertain (fuzzy) conditions. In computer terminology, “fuzzy” indicates neither true nor false, but something in between. Fuzzy logic provides a theoretical basis for the implementation of expert systems, where it has been most widely deployed to address nonlinear problems that cannot be solved using traditional Boolean (true/false) logic. Examples of building faults that might benefit from fuzzy logic include diagnostics for partially fouled condenser tubes or a somewhat dirty filter. As with expert systems, the undesirable probability of detecting false positive fault conditions with fuzzy logic is a problem that needs to be addressed. Section 4.1.5, “Types of Control Actions”, discusses neural networks in further detail.

4.2.1.2 Data Driven Methods

Data driven methods, including pattern recognition methods, are primarily empirical, although they can incorporate elements of first principles-based methods. They rely heavily on training data sets, which contain both system inputs and their corresponding outputs, to develop (“train”) viable models of the relationships between inputs and outputs. A building-related example would be recognition of faulty economizer operation. In this case, the model could recognize faulty operation by examining outdoor and mixed air temperatures and determining the conditions that indicate faulty operation. Subsequent monitoring of temperature data would compare operating conditions with the recorded pattern or signature for faulty economizer operation to assess the state of the economizer. These patterns can be developed using purely empirical methods, or using both empirical and first principles-based knowledge. Parametric methods use both empirical and first principles-based knowledge, whereas nonparametric methods are based only on empirical knowledge (PECI 2003).

Obtaining suitable training data for these methods can be very problematic. A useful training data set needs to reflect data captured from properly operating[11] building systems over most of the building operating conditions. Buildings differ from each another sufficiently in terms of design, operating patterns and environmental conditions sufficiently that training data often are building- and system-specific. Consequently, each building (and more complex systems) often must develop unique training data. A commissioning agent could, in theory, alter the building’s operation to mimic certain building faults. It is, however, unlikely that a commissioning agent would have sufficient time or opportunity to alter building operation to generate adequate training data, particularly if these data were to serve as the primary method for detecting faults. Alternately, computer simulations could provide training data; however, there are challenges related to simulating faults (as mentioned in the *Simulation-Based Methods* section).

Data driven methods tend to be applied to systems with poorly developed performance models that also have a wealth of training data available.

Statistical Methods

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[11] This requirement makes building commissioning essential before developing training data, as faulty operation will corrupt the training process and compromise its usefulness.

Statistical methods can identify patterns in the relationships between system inputs and outputs. Examples of parametric statistical methods include linear regression, and logistic regression, while cluster analysis and decision trees are nonparametric methods. Parametric methods are usually simpler – and therefore easier to develop – than nonparametric methods. In addition, they often perform better in applications that have little or no training data. The ability to tune parametric models to training data from the building makes these methods promising for AFDD / automated and continuous commissioning applications. All statistical methods require training data and can infer system inputs from system outputs. When little or no training data are available, statistical methods may not be appropriate. After successful commissioning of the HVAC system and several weeks or months of normal operation, continuous monitoring of the system's performance would become an appropriate application for statistical methods.

The best statistical method for a given application depends on several factors, such as the whether the purpose of the commissioning is classification (determination of state, e.g., functional or non-functional) or estimation (a quantitative assessment, e.g., percent efficiency degradation). Classification applies one of a finite number of labels to an observation, such as *normal* or *abnormal*. Estimation, on the other hand, applies one of a potentially infinite set of numerical labels to an observation, such as the cooling tower approach temperature exceeds the predicted approach temperature by 8.3°F. Both methods are valuable in automating fault detection and diagnostics. Classification can provide information in classes, or labels, that map directly into conclusions or actions, while estimation tends to be better suited to situations that demand numerical precision or high resolution (Briggs 2001). A statistical method might develop a mathematical relationship between whole building energy consumption and explanatory variables (e.g., daily outdoor air temperatures, day of the week, month of the year) and compare actual to expected energy consumption to detect excessive whole building energy consumption.

Artificial Neural Networks

Section 4.1.5, "Types of Control Actions", discusses neural networks.

4.2.2 Commissioning FDD

VTT (2001) defines FDD tool commissioning as: "the setting up, putting into operation, testing and maintaining of an FDD tool on a specific system, so that it can work according to its specification." Tool commissioning does not include commissioning of the building plant or control and communications systems to make sure that systems function properly, a process often required before tool commissioning can occur. They divide commissioning into four phases (see Table 4-5).

Table 4-5: Description of Commissioning Phases (based on VTT 2001)

Phase	Description
Setup	• Tool documentation • Are data about relevant equipment and systems available? o Equipment and system parameters o Plant and controller configuration o Controller parameters (set points, schedules, operational modes, etc.) o Site-specific data needed? o Simulation data needed? • FDD parameter settings (what they are, how to select) • Fault model data • Are requisite data available? o Measurement validation (acceptable quality, frequency, format) o Addition of sensors? (type, accuracy)
Putting Into Operation	• Acquisition of training data • Selection of FDD parameters and thresholds (guidance on selection process, relationship of parameters to false alarms, missed faults) • User interface (data visualization)
Testing	• Validation of FDD operation o Fault-free test procedure o Sensor validation (data quality acceptable for tool function) • Introduction of faults to validate tool function • Refinement of threshold settings
Maintenance	• Refinement of settings based on actual function • Validating/Maintaining sensor function and accuracy

The *setup* phase involves making sure that the FDD tool has the information about the monitored systems/equipment, receives the necessary data, and that the data are of sufficient quality for the tool to function properly. *Putting into operation* focuses on establishing the functional baseline parameters for the tool, i.e., acquiring training data (if needed) and selecting initial FDD parameters for that specific installation. During the *testing* phase, the team implementing the tool establishes the basic function of the tool by evaluating tool performance under no-fault conditions and, in some cases, in response to introduced faults. Refinement of alarm thresholds also occurs during this phase. *Maintenance* is an ongoing process to monitor and refine tool implementation in light of its actual performance (false alarm rates, missed faults).

Commissioning typically accounts for a large portion of the cost to implement FDD tools, particularly in larger and more complex systems or equipment whose performance depends on the specific installation details. On the other hand, equipment that is relatively self-contained and whose function depends less on the application context, such as rooftop air conditioning units (RTUs), may require far less commissioning. For example, RTU diagnostics integrated into a unit at the factory would likely arrive for installation with the FDD functionality integrated in its controller and:

- Necessary sensors installed with acceptable data acquisition performance
- FDD and system functional parameters known (determined by the manufacturer via testing to develop training data)

- Fault and alarm threshold values established (perhaps with users able to select “low” or “high” sensitivity values)
- FDD messages displayed on the controller output at the RTU and at the EMCS, RTUs in-room control panel, or wireless communication to an enterprise network.

4.2.3 FDD Thresholds

Effective FDD tools use thresholds, i.e., minimum deviation from expected values for a measured variable (or value derived from measurements), to manage the frequency of false alarms. FDD false alarms occur when data uncertainties, data inaccuracies, or model limitations/flaws cause the tool to determine that a measured variable has exceeded its threshold and diagnose a fault when, in reality, one has not. At least three different kinds of thresholds exist (VTT 2001). A *fault detection* threshold finds that fault has arisen when the difference between a measured and predicted control variable exceeds the threshold. In contrast, *alarm generation thresholds* indicate a fault when the probability of a fault has occurred exceeds the threshold. *Mode detection thresholds* determine the operating mode of a system based on the value and/or variability of at least one control variable relative to a threshold for each value and/or its variability.

Threshold selection tends to be difficult and has a significant impact on the usability of FDD tools. Choosing overly aggressive (low) thresholds tends to increase the frequency of false alarms. If false alarms occur too often, this imposes the cost of investigating the false alarms, erodes user confidence, and can cause users to ignore or abandon the tool. On the other hand, excessively high thresholds can cause the tool to overlook all but the most severe faults, which also limits the value of the tool. Consequently, effective threshold selection is crucial for effective deployment of an FDD tool. VTT (2001) describes three basic approaches to develop appropriate thresholds (see Table 4-6). In most cases, allowing tool users to vary fault detection thresholds to achieve an alarm rate that does not exceed the ability of the user to cope with the problems increases the usability of the tool (VTT 2001).

Table 4-6: Approaches to Develop FDD Thresholds (based on VTT 2001)

Approach	Characteristics
Heuristic	• Initial selection based on expert knowledge of system • Trial and error process to evaluate thresholds (after developing training data) • Trial and error process needs to be applied to all potential operating regimes
Statistical	• Thresholds based on confidence intervals and hypothesis testing using estimates of means or residuals’ standard deviations • Training data often used to estimate means and standard deviations • Good training data quality essential because it is used to develop thresholds
User Selection	• Allows user to adjust thresholds to obtain application-appropriate detection sensitivity and false alarm rate • Some users may adjust thresholds to the point where few or no faults are detected (“turn down the noise”), negating FDD value • Tool may exhibit greater/less sensitivity to certain faults – users may tune threshold for all based on a single fault, which decrease FDD effectiveness for other faults[12]

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[12] Multiple thresholds can help to address this problem, but this increases FDD complexity.

HVAC systems often exhibit non-linear behavior that can lead to different uncertainties and, hence, require different FDD thresholds over a range of operating conditions (implemented via expert rules, for example). Unsteady (non-steady state) behavior can also increase alarm frequency and some FDD schemes require detection of a fault condition for a minimum period of time before an alarm arises. Using multiple criteria to develop and confirm a diagnosis tends to improve the accuracy of FDD (VTT 2001).

4.2.4 EMCS Diagnostics

Almost all EMCS have the capability to perform some basic system- and equipment-level diagnostics (see Table 4-7). EMCS diagnostics capability, however, tends to be limited to basic functionality (e.g., compressor failure) and manual diagnostics. Consequently, a survey of larger office building operators found that responding to occupant complaints and routine inspections uncovered a much larger portion of building problems than examination of EMCS data (81% versus 19%; Gordon and Haasl 1996).

Table 4-7: Examples of More Common EMCS Diagnostics (based on McGowan 1995)

Diagnostic Capability	Description
Compressor Status	Typically for compressors >20 tons
Air Handling Unit Filter Clogging	Larger filters; based on differential pressure
Condenser Tube Fouling	Cooling towers; based on differential pressure
Simultaneous Cooling/Economizer and Humidifier Operation	Humidifier installations

Most EMCS enable operators to set *threshold alarms* for a measured control variable. When the control variable falls outside the specified range, the operator receives a message. If an operator suspects a problem, e.g., based on an alarm, he can manually select a control variable via the EMCS and observe its time history. HVAC systems often have *feedback alarms* that confirm that equipment reacts properly in response to a command from the EMCS. For instance, a feedback alarm would indicate that an air handling unit has not started up after receiving a command from the EMCS to start up (Blanc 1999). Multiple alarms, however, can inundate operators and cause them to ignore the alarms (“turn down the noise”) until a problem arises that requires immediate attention, e.g., a complaint call or equipment failure. Most EMCS, however, appear to not have appreciable diagnostics capability beyond indication of basic functionality (ON or OFF) and threshold alarms.

Researchers began developing diagnostic methods to evaluate HVAC system performance (not just function) in the 1980s and commercial diagnostic tools came to market in the late 1990s (Friedman and Piette 2001). A review of existing diagnostic tools found that most offered a range of data visualization capabilities (see Table 4-8).

Table 4-8: Common Data Visualization Methods Found in Diagnostic Tools (based on Friedman and Piette 2001)

Data Visualization Method	Description
Time Series	• Look at time history of one or more variable to spot anomalies
X-Y Plots	• Plot of two variables against each other to observe interdependencies
Three-D	• Three-dimensional (variable) plots to visualize interdependencies
Daily Profiles	• Plotting a control variable as a function of time-of-day for one or more days to spot anomalies
Load Duration	• Create a histogram of load or load factor for different loads to assess usage or sizing
Filtering	• Sort variable using user-defined data filters (e.g., day, time of day) to spot anomalies and correlations
Real-Time	• Plots data in real time
Aggregate	• Sums data from several systems or over time

Data visualization increases the user's understanding of building function and helps them to extract information from raw data recognizing operational anomalies and diagnosing faults through comparison with baseline data. They require, however, that operators have the knowledge to recognize faults from the graphs and information generated by the tool. Furthermore, building operators often are too busy to examine detailed data to effectively use the tool (Selkowitz 2003). Almost all EMCS have the capability to allow operators to perform rudimentary manual diagnostics, such as trend analysis of building data. EMCS, however, often have had limited data archiving and presentation capabilities because they historically have emphasized basic equipment function instead of detecting performance degradation or identifying opportunities to improve operational efficiency (Friedman and Piette 2001, Santos 2004). Over the past decade, energy information systems[13] (EIS) have come to market. This software facilitates data visualization, such as real-time EMCS, whole building (from interval meters), or submetered electric data, that can be used to develop performance benchmarks and carry out manual diagnostics (Motegi et al. 2003a).

Many diagnostic tools and EISs use manual diagnostic tools to identify problems by comparing actual performance to that found in other buildings or predicted for the system (see Table 4-9).

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[13] EIS, also known as enterprise energy management systems, developed as a way for utilities and building operators to monitor and curtail electric demand.

Table 4-9: Manual Diagnostic Methods in Diagnostics Tools (based on Friedman and Piette 2001)

Diagnostic Type	Description
Reference Line	• Compares actual performance with appropriate reference performance (e.g., from system model)
Benchmarking	• Comparison of (usually building-level) data with data taken from other buildings
Performance Metrics	• Calculated summary values, e.g., COP or kW/ton
Statistics	• Generates top-level values for variables: maximum, minimum, average, standard deviation, etc.

For instance, comparing actual chiller energy consumption at a given temperature to benchmark data for the building can provide insight into current chiller effectiveness. Most facility managers of larger office buildings, however, do not appear to perform simple energy consumption benchmarking (e.g., Btu/ft^2 or kWh/ft^2) or share monthly electric bills with the building operators (Gordon and Haasl 1996).

On the other hand, diagnostic tools tended to have fewer true automated diagnostic capabilities. Table 4-10 provides a feel for the capabilities of the most sophisticated automated diagnostics tool evaluated, applied in the context of a large commercial building.

Table 4-10: Representative Capabilities of a Sophisticated Automated Diagnostic Tool (based on Friedman and Piette 2001; Facility Dynamics 2003)

Diagnostics Level	Problems
Whole Buildings	• Deviation of energy consumption from expected (modeled) levels
Central Plant	• Chiller Diagnostics – Inappropriate chilled or return water temperature – Inefficient chiller staging – Poor load factor (running at very low load) – Subpar condenser and evaporator performance (e.g., due to fouling) – Efficiency degradation – Excessive cycling – Power draw different from expected (modeled) levels • Hydronic Distribution – Valve failure – Low temperature difference – Poorly performing pumps and vales – Primary/secondary loop problems (e.g., reverse flow) – Leaking valves (valve commanded shut, but heating or cooling occurring)
Air Handler	• No economizing • Excess / insufficient outdoor air • Simultaneous heating and cooling • Excess cycling of system components
Zone	• Logging of temperature, humidity and CO_2 levels
General	• Alarming • Failed outputs • Operator override • Run-time thresholds met (e.g., recommended maintenance interval) • Suspect, failed or mis-calibrated sensors • Unoccupied Operation • Unstable Control

Typically, automated diagnostics tools use some combination of statistical tools and expert rules to interpret building systems data and develop accurate diagnoses (see Section 4.2.1 for more discussion of diagnostic methods). For example, all the diagnostic tools evaluated by Friedman and Piette (2001) use air-temperature measurements to assess economizer function. In practice, small errors in temperature measurements can yield significant errors in implied economizer function and lead to improper diagnoses and false positives. To avoid these potential problems, the more sophisticated tools applied statistical tools and/or expert rules to reliably identify a fault and its cause, develop a recommended action to resolve the fault, and estimate the cost impact of the fault.

More recent direct digital controls (DDC) EMCS have the inherent potential to monitor many aspects of building performance. In practice, however, EMCS do not realize their diagnostics potential due to data access and data quality issues (low accuracy, missing data), and a lack of user-friendly diagnostics capability. All of these issues stem, in larger part, from the fundamental focus of EMCS design on controlling building systems instead of diagnosing building problems. The selection of measurement points usually reflects this priority. Consequently, an EMCS may not obtain the data needed for an effective diagnostics tool and adding diagnostics capability may require additional points (Friedman and Piette 2001). For example, the most sophisticated diagnostics tool requires at least nine different data inputs to diagnose economizer faults[14]. This increases the cost of diagnostics implementation, particularly in existing buildings that require running additional wiring for the new sensors. Even if an EMCS has the data points required for diagnostics, inferior data quality can prevent effective function of a diagnostic tool. EMCS often have improperly commissioned or un-commissioned sensors (Motegi et al. 2003) that can lead to incorrect diagnoses. Another common problem is missing data[15] from EMCS, which can prevent diagnoses altogether. Finally, EMCS typically do not have sufficient data storage capability to perform diagnostics based on longer-term performance trends (Friedman and Piette 2001). In principle, an EMCS could easily incorporate much more data storage – the cost of which has decreased dramatically over the past decade. In practice, however, this does not appear to be a cost barrier but another consequence of building control-centric EMCS design (instead of diagnostics).

If an EMCS can acquire the needed data and has sufficient data archiving capability, most have the potential to support building diagnostics, particularly data visualization techniques to analyze performance equipment and system performance trends[16]. A lack of user-friendly diagnostics capability, however, often impairs implementation of even basic data visualization techniques. Because most EMCS do not have embedded automated

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[14] Based on data presented for PACRAT in Friedman and Piette (2001).

[15] Friedman and Piette (2001) note that control system bottlenecks can cause missing data, e.g., from trending too many points at too high a frequency.

[16] In buildings without an EMCS, data loggers can collect shorter-term data to enable performance evaluations. Most larger commercial buildings, however, appear to lack data loggers (Gordon and Haasl 1996).

diagnostics, the operator must take the additional time to transfer the data from the EMCS into a separate diagnostics program run on a different PC (Friedman and Piette 2001).

Recently, EMCS vendors have begun to offer more sophisticated data visualization (manual diagnostics) tools, including time histories and state (relative to alarm states) of equipment and system variables (e.g., Johnson Controls 2001). Several EMCS vendors do offer remote diagnostics services, where they analyze data sent from an EMCS to assess system and equipment performance and diagnose problems (e.g., see Mueller 2003). In general, EMCS vendors have placed relatively little effort into developing or promoting data trending and archiving capabilities in EMCS. Tellingly, an appreciable portion of controls technicians appear not to be familiar with the trending capabilities and data archiving routines of EMCS made by their company (Santos and Rutt 2001).

4.2.5 Equipment-Level Diagnostics

As discussed in the prior section, an EMCS can monitor the status and performance of building equipment. Major HVAC equipment, notably chillers and rooftop units, usually incorporate diagnostics that monitor the status of major components at the equipment level as well as filter pressure drop (PG&E 2000). For example, a larger packaged RTU[17] produced by a major manufacturer indicates the status of the following components: compressor, blower motor, evaporator fan motor, heat status, and all temperature sensors. The same unit displays information that can help a service technician to diagnose the reason for failures. Smaller units[18] may have optional configurations that can incorporate a more limited set of functional status monitoring, such as heating and cooling status, and evaporator fan and economizer operation.

At least one controls manufacturer offers a portable suite of temperature and pressure sensors that technicians can attach to different portions of the refrigerant cycle to monitor the unit's[19] operation. Based on the measurements, diagnostics software evaluates the unit's performance, diagnoses faults that degrade performance, and estimates the annual energy impact of the fault. Although the use of portable instrumentation limits its application, the sophistication of the fault detection clearly goes beyond the standard functionality monitoring incorporated into equipment. Importantly, it leverages the cost of the diagnostics over multiple pieces of equipment, which reduces the effective per-unit cost of the diagnostics suite. Section 9.8 discusses this diagnostic approach in further detail.

4.3 Building Controls Communications

Communications play a major role in enabling controls, particularly building-wide digital controls. Communication protocols dictate how devices communicate with each other and

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[17] The Carrier 48Z series, from 30 to 105 tons. Information available at: http://www.commercial.carrier.com/wcs/dynamiclit_result/1,1825,CLI1_DIV12_ETI4906_PRD3,00.html?SMSESSION=NO .

[18] For example, the Carrier 48TM series, from 3 to 12.5 tons. Information available at: http://www.commercial.carrier.com/wcs/dynamiclit_result/1,1825,CLI1_DIV12_ETI4906_PRD558,00.html?SMSESSION=NO ,

[19] This applies to packaged air-conditioners, split air conditioners, and heat pumps operating in cooling mode. Information available at: http://www.acrx.com/ServiceAssistant.htm .

are central to the question of interoperability, that is, whether or not devices can share essential information to allow effective control function. Communications media denote the physical media that convey control information and commands between devices, e.g., twisted-pair wiring, and have a substantial impact on the installed cost of building controls. Several advances have occurred in both areas over the prior two decades, particularly in protocols, with major ramifications for the functionality and cost of building control systems. The following two sub-sections discuss communications protocols and media, respectively.

4.3.1 Communications Protocols

Some building controls can operate effectively in a stand-alone mode, such as occupancy sensor-based lighting control. Building controls operating on a building-wide scale require communication between the different sensors, actuators and controllers to carry out appropriate control actions. The advent of direct digital control (DDC) began the transition from pneumatic to electronic communications and markedly increased the ease of information feedback and exchange between points. This, in turn, allowed a much greater range of potential control strategies while providing superior reliability.

Initially, almost all DDC systems relied upon proprietary communications protocols from major building-controls vendors that could effectively communicate with the proprietary EMCS. As a consequence, owners were locked into a single equipment vendor. In the 1990s, customers began to demand “open” communication protocols that would allow them to consider and select equipment, sensors, and control software with the most attractive features for each building. Open standards-based approaches increase competition for the provision of hardware and services, which could reduce the first and ongoing costs of building control systems. In addition, open standard should lower barriers to entry and provide access to a wider range of functionality. This approach should reduce, most notably, the cost of network gear (commodity IT equipment), as well as central and distributed control points (sensors and actuators), control procedures/algorithms, maintenance, and installation.

In this environment, several open communications protocols came to market, with BACnet ™ and LonTalk® receiving the most attention in the U.S. market. Although either BACnet ™ or LonTalk® can be used to realize interoperability, they are not interoperable with each other. Table 4-11 compares different building automation protocols.

Table 4-11: Top-Level Comparison of Different Building Automation Protocols (based on CABA 2002b)

Protocol	Markets Served	Market Presence
BACnet	Building monitoring and control systems: HVAC, fire alarm and detection, lighting, access	Over 180 vendors[20]; >125 products have received BTL listing (as of August, 2005[21])
LonTalk	Building systems: HVAC, fire alarm, lighting, access, vertical transport, home automation, automated food service; Refrigeration; Transportation; Utility (metering), Appliances; Industrial	Over 400 certified products; thousands of manufacturers
Modbus	Power Monitoring; SCADA; Energy Metering; Engine-Generator Control/Monitoring	Total of 69 Registered Serial and TCP/IP Modbus devices[22]; more than 300 manufacturers
EIB	Building Automation and Control: Lighting, blinds, heating, home automation	Over 6,000 certified and registered products
KNX	Building Automation and Monitoring: Fire, HVAC, home automation; Utility (monitoring); Appliances	KNX certification only recently begun; fully compatible and interoperable with EIB products; "thousands" of companies

Initially, there were many more manufacturers of LonTalk®-based devices for building applications (Kranz and Gisler 2002), e.g. circa 2003 there were hundreds of LonWorks device manufacturers and at at leastbut only five mainline BACnet™ vendors (Ruther 2003). Over the past two years, the number of manufacturers producing BACnet™ products has increased dramatically, to at least 181[23]. vendors. Thus, LonTalk® devices should provide a broader range of potential functionality as well as more competitive device pricing. LonWorks® products appear to have gained greater market share for equipment control and stand-alone controllers than BACnet™ (DeNamur 2002). On the other hand, Kranz and Gisler (2002) believe BACnet™ represents the best option for EMCS control because it offers greater top-level functionality and interoperability with enterprise networks (i.e., with Ethernet and IP). Long-time industry analysts believe that reliable information about the relative market shares of different communications protocols is not available (BCS 2002). Proprietary communications protocols, however, may still account for over half of building controls market sales (Callahan 2003, Sullivan 2003b). The following discussion of open communication protocols focuses on BACnet ™ and LonTalk® because of their standing in the marketplace, as well as rapidly-evolving efforts to integrate building controls into enterprise networks. It also includes a separate sub-section on lighting control protocols. Section 4.3.2.1 discuss wireless communication systems and protocols.

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[20] A list of BACNet vendors can be found at: http://www.bacnet.org/Gallery/index.html . In practice, the number of vendors may be substantially larger (see: http://www.bacnet.org/VendorID/).

[21] Listed products from: http://bacnetassociation.org/btl/AllManufacturerStart.htm . Additional BACnet™ products likely exist that are not listed.

[22] From http://www.modbus.org/default.htm ; information accessed on 18 June, 2003.

[23] Based on the list of distinct BACnet™ vendor ID's as of 25 August, 2005 (see: http://www.bacnet.org/VendorID/).

4.3.1.1 BACnet™

BACnet™, short for Building Automation and Control Networks, is an object-oriented standard that represents all communication information and defines how automation and control systems can operate with other BACnet™ systems. Work on BACnet™ development began under the auspices of ASHRAE circa 1987; as a result, BACnet™ systems are most common in HVAC systems, particularly centralized systems. ASHRAE, ANSI and ISO have all adopted BACnet™ as a standard. It offers the potential for inter-operability, but all BACnet™-compliant systems must implement relevant BACnet™ features required by other systems. This tends to be where BACnet™ interoperability falls short (CABA 2002a). In other cases, problems have arisen from improperly specified data fields, e.g., not clearly identifying a value as a temperature or as a setpoint (Levi 2003). To increase the potential for interoperability, the BACnet™ standards committee released an annex (Annex L) that focused on specifying minimum capabilities to realize functions seen as crucial to interoperability. These include data sharing, alarm and event management, scheduling, trending, and device and network management. A vendor can claim that a given device meets the profile demanded by Annex L, and therefore give building system designers confidence that the device can meet basic interoperability functionalities. In the future, BACnet™ may expand to integrate other, non-HVAC systems, such as lighting controls, utilities integration (e.g., for real-time pricing signals), and building access control (Bushby and Newman 2002).

4.3.1.2 LonWorks®

The Echelon Corporation (with Motorola) began LonWorks®[24] development in the 1980s. LonWorks® represents a family of products that require a proprietary communications chip for implementation. LonWorks® devices use the proprietary communications protocol LonTalk® messages contain data objects that “are defined according to multiple structures. The structures are identified by code numbers that form part of the data stream and allow the receiver and the sender to interpret the data stream in a common manner” (CABA 2002a). LonWorks® does *not* define the code numbers, i.e., each vendor can define and interpret them differently, leading to lack of compatibility between vendors. In time, vendors agreed to conform to conventions set by the LonMark® consortium. As a result, some – but not all – LonWorks® products/systems are LonMark®-compliant and capable of interoperation. In contrast to BACnet™, whose development focused on HVAC systems, LonWorks® has targeted several markets relevant to building system integration. Consequently, many expect that LonWorks® will likely play a larger role than BACnet™ integrated systems (e.g., fire, elevators, security, etc.).

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[24] LonWorks® is the network framework within which the LonTalk® protocol works; both are based on guidelines developed by the LonMark Interoperability Association.

4.3.1.3 Enterprise Networks

Recently, the building controls market has begun to exploit enterprise networks to communicate information. This can reduce the installed cost of building controls by using a single, shared communications infrastructure (be it wired or wireless) instead of two separate networks. The functionality of enterprise networks, notably their ability to efficiently move information, facilitates cost-effective deployment of new functions such as remote access or control of an EMCS. For example, a building operator could remotely access data and control a building from any device with Internet access (PC, hand-held device, cell phone) and appropriate access permission. The same operator could also port building data to a PC for further analysis, e.g., data trending, pattern recognition or to carry out diagnostic or alarm function. In the future, the trend toward communications over enterprise networks could devolve much control of occupied space to building occupants by allowing control of the environment (temperature, light levels, etc.) over existing enterprise networks via web browsers; to a very limited extent, this has already begun to occur, e.g., the deployment of "virtual thermostats" on PCs noted by Tom (2005). This would tend to increase occupant comfort (see Section 7.1)

A web-based system[25] that uses the same communications language and infrastructure facilitates the sharing of information and communication essential to building integration. They also simplify the sharing of information between business systems (which often transmits information in internet protocol [IP]) and building systems, because the building systems then share the same "language" as the business systems. Other protocols require "translation" between systems for effective communication. For instance, a hospital with web-based communications and building systems can readily link patient status to room occupancy, i.e., to change the space conditioning set point and lighting based on occupancy. At the same time, the system can ensure that the room selected for a patient meets the specific needs of the patient, e.g., infectious disease isolation (Hill 2003). The seamless sharing and transfer of information via IP (or other protocols) can also substantial increase the efficiency of building management. For example, a study of U.S. capital facilities estimates that seamless interoperability increases operations and maintenance costs by $\$0.23/\text{ft}^2$, or about \$9 billion annually. Time used to verify the accuracy of information (~53%), time spent waiting for information needed to address maintenance issues (~17%), and inefficient information business process management (~18%, from documentation management, maintenance planning management, etc.) accounted for most of the estimated inefficiencies (Gallaher et al. 2004).

To leverage these possibilities, communications protocols incorporate specifications to communicate over IP networks. For example, ASHRAE published an annex to the BACnet$^{\text{TM}}$ standard in 1999 known as "BACnet/IP" that specifies how BACnet$^{\text{TM}}$ devices can directly communicate over any IP-based network. Major EMCS vendors now offer

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[25] According to a VP with one of the "Big Three" building controls manufacturers, products that adhere to the Web Services Interoperability Organization (WS-I – find out more at: http://www.ws-i.org) standards and protocols can be integrated into a web-based system (Hill 2003).

"BACnet^{TM}/IP" workstations and building controllers that some see as becoming the primary mode of BACnet^{TM} networking[26] (Bushby and Newman 2002). Impending advances in internet protocol, notably IPv6 and IPsec, will further enable data communication and system security in building controls (Grossetete 2004). IPv6 allows a virtually unlimited supply of IP addresses and IPsec is a more secure internet protocol.

Ultimately, building controls may communicate entirely in IP-based protocols, bypassing the need for other protocols. Indeed, the "big three" building controls manufacturers all have EMCS capable of communicating in transmission control protocol / internet protocol (TCP/IP). Web-base building control systems that use eXtensible Markup Language (XML), a data format for sharing device-specific information over enterprise networks, are under development and at least two manufacturers have launched native XML building control products[27]. This does not, however, obviate the need for clear definition of the intent of shared information. For instance, an EMCS could send a command to a digital outdoor lighting controller to dim the lights, but the lighting controller needs to receive the information in a format that it can understand. For example, the lighting controller must know that the incoming data tells the controller to dim the light to a specified level. The development of appropriate XML *schema*, which provides agreed-upon terms for clear communication of intent between devices for a set of applications for building control, would address this issue. ASHRAE Guideline Committee 20 is pursuing development of appropriate XML schemas for a broad range of HVAC applications[28]. Concerns about the duration of the ASHRAE process have led the Continental Automated Building Association (CABA) to form the Open Building Information Xchange (oBIX, formerly the CABA XML/Web Services Guideline Committee[29]) to develop XML- and web services-based for key information used to control and monitor buildings. The development of several different XML definitions, ironically, could inhibit widespread use of XML because it could perpetuate the existence of several distinct protocols that are not interoperable (Beverly 2004). A roundtable discussion by automated building executives concluded that XML standards and technology will enhance data management and sharing but probably not displace LonWorks or BACnet devices (Sinclair 2003).

OPC[30] is another possible way to standardize the communication of information between different applications (programs). It defines standard objects, interfaces and methods for specific automation applications for information exchange between applications, such as controllers.

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[26] Hollinger (2004) notes that several potential areas of improvement exist, including network security, interoperability with network components, and network performance.

[27] Reiss (2003) found that, as of late 2003, only Johnson Controls, Inc. had launched a building controls product in native XML. The Metasys EMCS product incorporates Microsoft .NET application, which uses XML. As of January, 2004, Honeywell also had an XML-based EMCS product.

[28] Considine (2005) expects publication by 2007.

[29] For more information, please see: www.obix.org .

[30] Object Linking and Embedding (OLE) for Process Control. More information available at: www.opcfoundation.org . Smaller devices could use a chip-based version called Simple Control Protocol (SCP) (CABA 2003a).

The extension of Universal Plug ‘n Play (UPnP) to commercial building control applications and devices could facilitate the startup (and, potentially, commissioning) of building controls. UPnP is an open technology that allows IP-based communication between UPnP-enabled devices on a network that supports IP. It incorporates a discovery function that largely automates the incorporation of new UPnP devices into the network. When a new device is added to the network, it “advertises” its presence to the other UPnP-enabled devices. The devices exchange information about their functionality (in XML format), which then enables devices to share information or allow one device to control another device. To communicate the relevant information for an application, each specific type of device needs to have a template that indicates the key device-specific information/characteristics to be defined to enable it to function fully. Individual manufacturers can define additional definitions (types of information) for their UPnP-enabled devices to extend the capabilities of the device. Typically, each industry defines templates for devices in their industry (Steinfeld 2001). The UPnP forum has developed standards for the descriptions, services and data used by some basic lighting and HVAC devices[31], but it is not clear that they have yet seen appreciable use with commercial building control systems. Currently, UPnP exists more at the configuration level, that is, some devices contain the data needed to configure them, which enables configuration via a web browser (McKissack and Zebrick 2004).

Assuming that building controls manufacturers develop UPnP templates for building control devices and implement them in actual devices, UPnP would reduce the time required to commission controls networks. For example, a contractor would install an UPnP-enabled economizer controller that would advertise its presence to the UPnP-enabled[32] EMCS. The EMCS would then know that the economizer controller exists as part of the building control network. In addition, it knows the functionality of the economizer controller, that is, what the economizer can do and the acceptable kinds of commands and outputs, and control information that it can generate and accept (as defined in an XLM file, accessed via Simple Object Access Protocol [SOAP]; Steinfeld 2001). The building controls vendor could add features to a device, such as enabling an economizer controller to monitor the outdoor air temperature sensor calibration status, by creating the additional definitions needed in the UPnP-enabled temperature sensor and controller.

Power over Ethernet (PoE) represents another potentially promising application of enterprise network technology to buildings. As codified by IEEE802.3af, PoE can provide up to 13W of power over Ethernet cabling to devices up to 100m from an Ethernet hub or port (Thomas 2005). Thus, it consolidates separate communications and power wiring into one connection, reducing the cost of installing a wired device. In buildings, for example, it could potentially power and provide information to and from sensors and some controllers. It is not clear, however, if and when PoE will become cost-effective for devices that

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[31] See: http://www.upnp.org/standardizeddcps/default.asp .

[32] And likely web-enabled; a person or another device can interact with UPnP-enabled devices through a web browser or a via programming.

currently use low-cost low-voltage wiring for data signals because the device-level infrastructure required to support IP communications increases their cost.

If building control does migrate to enterprise networks, cultural differences between IT and facilities departments may create implementation problems. For example, the relative ease of access to information on IP-based networks has numerous ramifications for building security, e.g., access to building information, building control functions, and the building itself (via the access control system). To date, facilities managers have focused on physical security while IT personnel have paid more attention to data security (Looney 2003).

4.3.1.4 Lighting Control Protocols

Although lighting controls have begun to be integrated with the controls of other building systems, most buildings continue to use separate controls for lighting. Futhermore, to date, different lighting control manufacturers have used different proprietary lighting control communication protocols. This limits the ability for contractors and end-users to consider and integrate lighting control products from multiple vendors (Sinclair 2003). Recently, the Digital Addressable Lighting Interface (DALI) has become a communication protocol for lighting control that specifies the communications between lighting controllers and fixtures. DALI uses line-voltage or low-voltage signals sent over dedicated communications wiring to the individual fluorescent lamp electronic ballasts, each with its own address. This enables centralized control (from a DALI controller or an EMCS) of individual ballasts or grouping of ballasts (up to 64), including multiple (up to 16) pre-programmed scenes). DALI devices also can provide feedback about lamp and ballast performance from ballasts to controllers, for instance, noting burnt-out lamps or failed ballasts. Although “widely used” in Europe (where it originated), it has had less success in the U.S. to date, i.e., very few DALI ballasts and controls exist in the U.S. (DiLouie 2003b).

Ultimately, DALI could enable greater personal control over lighting, e.g., via a web browser that communicates with the lighting system. DALI does not, however, enable communication between a lighting controller and an EMCS. The ability to affect ballast-level lighting control from an EMCS requires extending a building controls protocol, such as BACnet™ or LonTalk®, to enable the EMCS to communicate directly with the lighting controller which, in turn, communicates with the individual ballasts. The DELi lighting control module[33] integrates DALI networks with LonWorks®, while a BACnet working group is developing a new object[34] to allow the control of digital ballasts via centralized building controls. Lighting control protocols that communicate over micro-LANs protocols in attempt to reduce network costs are also under development (Treado 2004; Rubinstein et al. 2000).

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[33] See, for example: http://www.lonmark.org/products/datasheets/del_DELiT1-1E2-1E.pdf .

[34] As Treado (2004) explains, “the digital ballast object would have properties relating to each of the DALI ballast variables … dim level, minimum level, maximum level, fade time, etc.”.

4.3.1.5 Current State of Controls Interoperability

As noted earlier, proprietary controls still account for a majority of the building control system market. Some facility executives prefer open protocols because they believe that they facilitate building systems integration, increase the number of vendors considered for system upgrades, and reduce the cost of upgrades. Given that service costs for proprietary systems may cost approximately 35% more than open systems, it is not surprising that the desire to manage system service and upgrade costs ranks as the primary reason that people migrate from proprietary to open systems (Sullivan 2003b). On the other hand, executives expressed several reasons they continue to use proprietary systems (see Table 4-12).

Table 4-12: Characteristics of Open and Proprietary Systems (based on Sullivan 2003b and other sources)

Issue	Open Systems	Proprietary Systems
Cost	• Promise lower up-front cost; mixed experience in practice • Lower cost for upgrades • Need to manage several vendors	• Proprietary systems may have lower first cost as a “loss leader” • Higher cost for service and upgrades
Organizational	• Different organizational practice – need to understand pros and cons for that organization • Greater understanding of controls needed at all levels • More expertise/training required • Requires tight specifications to consider multiple vendors	• “Business-as-usual” option • Readily outsourced to single vendor
Responsibility for System	• Multiple vendors potentially used • System integrator a key figure	• System from single source

Despite efforts to develop interoperable systems based on open protocols, this goal generally remains elusive. A recent “Technology Roadmap for Intelligent Buildings” notes that “currently, adherence to standards and protocols that ensure interoperability among diverse systems does not generally exist in the marketplace for intelligent building technologies” (CABA 2002a; Kranz and Gisler [2002] note the same issue). Existing controls systems complicate integration of controls and/or building systems because they typically “speak” different languages over separate communication networks. Fire and life safety systems are more likely to have proprietary controls due to their critical nature. However, interoperability and integrated communications can be achieved by a single vendor or “middleware”, a universal translation architecture that bridges the communications gap between different systems (CABA 2002a).

4.3.2 Building Controls Media

Since the advent of DDC, twisted pair wiring has become the standard medium for communication. Typically, a different contractor installs each building system (HVAC, fire, security, building access, vertical transport, communications, etc.) at a separate point in time, with independent wiring/conduits and separate communications terminals for each system. In the context of integrated building systems, forward-looking parties have begun considering the possibility of sharing a single wiring installation. For example, structured cabling systems (SCS) that integrate cabling for all building systems could reduce the installation and capital costs of communications. The development of standards for cabling, such as ANSI/TIA/EIA-862, “Building Automation Systems Cabling Standard for Commercial Buildings” and ANSI/TIA/EIA-568, “Commercial Building Communications Cabling Standard”, has the potential to normalize cabling and connectors for building systems. Several benefits to building contractors and owners should result, including a greater range of vendors to select from and greater flexibility in making changes during system installation and in the future, e.g., system upgrades (CABA 2003b). One consultant that provides building planning, design and implementation and integration support estimates that SCS reduces the cost of cabling, cable ways, and maintenance by 20 to 30 percent (CABA 2003b).

The actual implementation of such an approach would require a major paradigm change in current installation practices. For example, an installation would require integrated communications planning at the project level that would take responsibility for: common infrastructure, infrastructure testing, acceptance, commissioning and testing; system selection, interaction, testing/commissioning, verification; documentation, servicing, maintenance, and repair. Ideally, communication hardware would be easy to upgrade. Buildings have a typical time between major renovations on the order of 25 years, while electronic technology life cycles are much shorter, approximately 5 to 10 years (CABA 2002a). This makes the ability to upgrade while using existing connections crucial.

In existing buildings, the cost of installing additional cabling to communicate with new sensors or to integrate existing sensors into an EMCS can be very high. This cost is, not infrequently, prohibitive due to the complexity of pulling and snaking wires through the existing structure. Two controls approaches, power-line carrier (PLC) and wireless, have received considerable attention as ways to overcome these issues. Powerline carrier sends control signals over the wires used to provide electric power to equipment, in this case lights. A transmitter encodes a control signal into a digital signal and transmits it at a frequency much higher (between 25kHz and 250kHz) than the electric power signal to receivers located at the controlled devices. Because PLC leverages the existing wiring infrastructure, it has the potential to reduce the installed cost of lighting controls, particularly in retrofit situations. On the other hand, the effectiveness of PLC can suffer from electrical noise or transients generated by devices connected to the same electrical distribution network (Knisley 2003). To date, PLC has primarily been used in residential markets. Long-term analysts of the building controls market do not, however, expect that PLC will play a major role in the larger building control market any time soon (BCS 2002).

4.3.2.1 Wireless

A variety of wireless communications approaches offer the promise of decreasing the installed cost of controls and diagnostics for several applications (see Section 9.5.4 for a discussion of wireless costs). In general, wireless communications can realize the greatest benefit in retrofit applications, most notably those that require longer cable runs and/or having problematic access, and need infrequent communication (limited power availability drives infrequent communication; Kintner-Meyer and Brambley 2002). Many options currently exist for implementing wireless systems in buildings. A "wireless sensor" cannot operate independently—it needs to be part of a "wireless system." Each implementation and each building has unique features that impact the type and quantity of wireless system components needed, and thus the total wireless system cost. Figure 4-4 depicts a generic wireless data acquisition system. In general, a wireless data transmission system will include transmitters and receivers, and a translator to allow the wireless receiver to communicate with a control network and, in the case of a central system, the building's EMCS. To help boost the strength of wireless signals, repeaters may be needed; the capabilities of the repeaters (e.g., whether they are simple repeaters or, instead, routers) depend on the type of wireless system (e.g., point-to-point, mesh).Wireless implementation may also require a radio frequency survey to assess acceptable operating distances between transmitters and receivers on-site (see, e.g., Zebrick 2003).

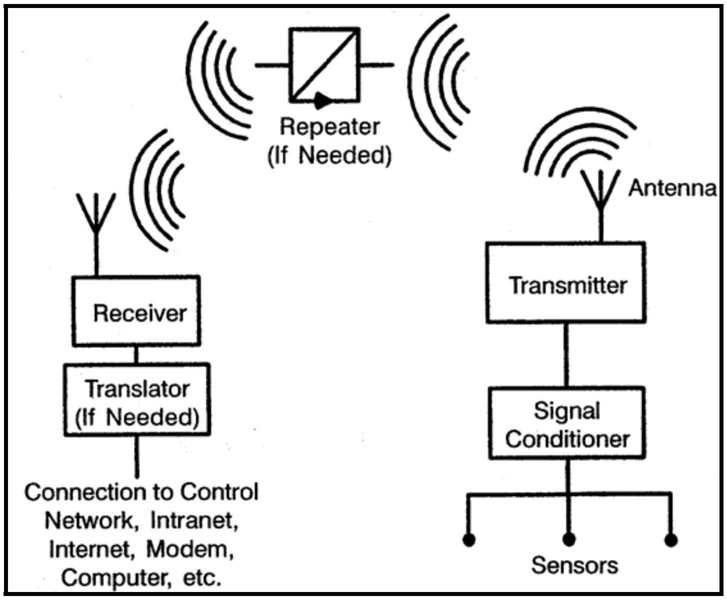

Figure 4-4: Components of a Generic Wireless Radio-Frequency Data Acquisition System (from Kintner-Meyer and Brambley 2002)

Recently, a wide variety of wireless-enabled sensor products have come to market, both within and outside of the commercial building HVAC industry, including warless temperature sensors offered by all of the "big three" building controls manufacturers. Some wireless "sensors" actually consist of a traditional (wired) sensor connected to a wireless transmitter. Other wireless sensors consist of a sensor integrated with a radio that broadcasts data to a receiver, transmitter, or another sensor (e.g., in a wireless mesh network). As wireless systems mature further and accommodate more definitively the HVAC market, they have the potential to significantly impact the building controls and systems communications infrastructure of the future. Although wireless technologies have begun to make inroads in commercial building HVAC systems, competing technologies provide multiple methods for wireless implementation. Consequently, a lack of standardization in systems implementation exists.

Wireless technologies range from simple “wire replacement” or point-to-point wireless schemes (Kele 2004), to interconnected, self-enabling and self-healing wireless mesh networks (see, for example, Kintner-Meyer and Conant 2004). Currently, wireless technology is experiencing tremendous advancement in several markets. Mesh networks—in which some or all nodes can serve not only as transmitters and receivers but also as routers that can relay messages for their neighbors (CABA 2004a; Turpin 2004)—are being deployed, for example, along with moisture and temperature sensors for agricultural monitoring (Delin 2004; Electronic News 2004). Industrial users are deploying sensors that are equipped for wireless communication (Marshall 2003). Wireless “wire-replacement” technologies for commercial buildings have existed for more than two years (Turpin 2004) and wireless systems compatible with BACnet are available (Wang and Nova 2004; Kiyon 2004). Very recently, EMCS and wireless mesh network providers are entering into business relationships with each other in hopes of serving the needs of commercial building HVAC systems (Turpin 2004).

Intriguingly, a major building controls manufacturer has begun offering a wireless solution that provides pervasive indoor wireless communications access via radio frequencies for several different applications, including building controls (see Table 4-13).

Table 4-13: Potential Communication Capabilities of the Johnson InnerMobile Wireless Infrastructure (Buckley 2004, Johnson Controls 2004)

Application	Comments
Building Controls	Data from wireless sensors to controllers or EMCS
Cell Phones	Potentially for 1G, 2G, 2.5 and 3G service
Digital Radios	
General Data Communication	Sales information (stores), patient information (hospital), etc.
Pagers	
Voice Over IP (VoIP)	Communications in IP via wireless LAN
Wireless Local Area Network (LAN)	Wireless Ethernet via 802.11b/g, e.g., for laptops and PDAs

It is conceivable that building owners might install this solution primiarly to provide cell phone and Wi-Fi service in buildings. In that case, building control applications would leverage the wireless infrastructure to communicate with receivers that communicate with building controls. For example, a temperature sensor could broadcast data in a proprietary format using a wireless radio protocol to the wireless infrastructure, which would then pass that information in IP over Ethernet to an EMCS that uses that information to help control the building. This would decrease the effective installed cost of measurement points for building control.

While the challenges and applications of using wireless communications for commercial building controls are well known, the types of wireless systems and the final implementation schemes that will find their way to wide market acceptance are as yet unknown.

Alternative wireless technologies employ various radio transmission frequencies, transmission modes, and data communication protocols (see, for example, Kintner-Meyer and Conant 2004). The frequency bands in which radios may broadcast is, in the United States, regulated by the Federal Communications Commission (FCC). Operation on the FCC-designated Instrumentation, Scientific and Medical (ISM) bands does not require a license and modern low-power digital radios can operate in these bands. The ability of radio transmissions to penetrate building constructions depends on the transmission frequency. In general, lower frequency signals travel farther than higher frequency signals, e.g., 900MHz signals will be less-attenuated by building constructions than will be 2.4GHz signals. Transmit-signal strength and the ability of the signal to penetrate building constructions both help to define the required spatial density of the wireless system components. The transmission frequency also affects the maximum possible data transmission rate. When choosing a frequency band for radio operation, the potential for interference from other signal and noise sources needs to be considered (e.g., Bluetooth, Wi-Fi, microwave ovens; Zebrick 2003, Wang and Nova 2004).

Radio transmission modes, i.e., the format in which the radio signals are sent, include the older narrow-band analog radio transmission mode and the modern digital direct sequence spread spectrum (DSSS) transmission mode. DSSS transmits the signal in multiple pieces over multiple frequencies, which are subsequently re-assembled at the receiver. This builds resistance to interference from electrical noise, and also increases security. Another approach to achieve wireless communication in buildings is to wire the building with antennas, thus allowing cell phone or computer Wi-Fi communications from anywhere in the building (Cantwell 2003). Data communication protocols, which determine the format in which data are sent, include Ethernet, BACnet, and wireless mesh network protocols (Adams 2003; CABA 2004a).

Currently, market forces have played the largest role in determining the communication standards and protocols that will persist and succeed in the commercial building HVAC market. No agencies or groups have stepped in to mandate any one wireless implementation (i.e., frequency band, radio transmission mode, communication protocol). One group promoting a standard is the ZigBee Alliance (Adams 2003). ZigBee is a standard for the wireless transmission of digital data at radio frequencies (800MHz, 900MHz, and 2.4GHz) that addresses many of the concerns about wireless communications in buildings. That is, it operates at low data rates to reduce energy consumption and prolong wireless sensor battery life, incorporates effective data security options, has good reliability, takes advantage of communication technologies to reduce interference, and has a low cost (Zebrick 2004b; Kintner-Meyer and Conant 2004). ZigBee conformance alone, however, will likely not prove to be a panacea for commercial building HVAC systems for at least two reasons. First, although ZigBee-compliant devices from different vendors may be able to communicate data between them, they may not be capable of correctly *interpreting* the data unless the devices use the same data formats (e.g., number of bits, measured units, kind of data contained in each data packet). This parallels compatibility issues that have arisen with XML for IP-based communications (see Section 4.3.1.3). Second, because 100% ZigBee-compliant systems use low-power transmitters, they may be able to communicate data only about 10 meters. In practice, many wireless applications for commercial building HVAC systems require greater transmit power to overcome attenuation caused by steel, concrete, furnishings, and people. Instead, hybrid systems formed from ZigBee-compliant components, along with higher power components that can communicate with ZigBee compliant components, may succeed in commercial building applications (Zebrick 2004a, Zebrick 2004b).

Power provision and consumption are other key considerations for wireless systems. Standalone wireless sensors use battery power and it is essential that the sensors conserve battery energy to reduce the recurring labor associated with battery replacement. For example, Kintner-Meyer and Conant (2004) estimate that a wireless sensor must have a 3– to 5–year lifetime at the least. Wireless sensor systems need to balance lower power draw against other sensor performance requirements for different applications. Lower power consumption can be achieved using longer intervals between signal transmissions in many, but not all, applications. This approach can be acceptable for sensors used for control of processes with longer time constants, e.g., a temperature sensor used to control space temperature might transmit data every 30 to 60 seconds (Zebrick 2003) and sleep when not transmitting data. Wireless sensors, however, would be less well suited for actuating lighting controls because the application demands very quick response to user input (Rubinstein 2004). Higher transmission speeds can also increase battery life, because high-speed transmissions reduce the "on" time for a transmitter (Adams 2003).

Another way to avoid battery replacement issues and circumvent low power consumption requirements, yet retain many of the benefits of wireless, is to use line-powered wireless sensors and repeaters. That is, the devices plug directly into the ubiquitous wall sockets instead of using hard wiring (Zebrick 2004a). Even though these sensors are not completely wireless, they still eliminate the need to run wiring between the sensor and a central control system. Other options under development to supply power besides batteries and line power include solar power and power scavenging[35] from sources, such as vibration and heat.

Some other challenges (besides first cost) to deploying wireless systems in commercial buildings today include:

- Security concerns (e.g., hackers);
- Potential need to administer the system, and
- Concern about the potential for a corporate mandate directing involvement of corporate Information Technology staff in the operation of HVAC wireless networks.

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[35] In particular, U.C. Berkeley researchers are performing significant research in power scavenging for wireless communications. See, for example, Roundy et al. (2004).

Many of the above challenges, e.g., security concerns or concerns about involvement of IT staff, are not unique to wireless (see Sections 4.3.1.3 and 6.5); nonetheless, these concerns are often voiced during discussions of concerns about wireless systems.

Ultimately, the success of wireless communications in commercial building HVAC systems depends on their ability to decrease the installed cost of sensors, whether those sensors are used to increase the functionality of existing control systems or to facilitate the installation of building controls in new buildings.

4.4 Energy Management Control Systems (EMCS)

Large building control systems first appeared in the 1960s, evolving from industrial process control systems into the mini-computer-controlled systems deployed in the late 1960s. Initially, they were deployed to reduce buildings operations and maintenance staff, but appeared in only the largest new construction where the high first cost of the system could be amortized over the entire building. Energy became a significant concern in the early- and mid-1970s due to the run-up in energy prices during the oil embargoes. This led to a shift in focus to manage energy consumption, hence the term energy management and control system (EMCS). Energy cost pressures increased the market share of EMCS, incorporating energy-saving functionality such as separate day and night schedules for HVAC and lighting, and demand control.

Systems used pneumatic communications and controls until the early 1980s, when direct digital controls (DDC) came to the building controls market. The “Big 3”, Johnson Controls, Honeywell, and Siemens dominated the market (~80% in the mid-1980s) with their proprietary systems. The move to electronic-based DDC, enabled by the dramatic increases in computing power and the concurrent miniaturization and cost decrease of computing power, lowered barriers to entry and placed a greater emphasis on the technical qualities of each system. In addition, software controllers began to supplant hard-wired control logic (e.g., electronic controller boards). This enabled many smaller players to enter the market and eroded the market share of the Big 3. In the 1990s, interoperability of systems became a significant concern of end-users, as they wanted to avoid becoming dependent on systems and components from a single vendor. Consequently, the market moved away from proprietary building control systems to open protocols, e.g., BACnet ™ and LonTalk® (BCS 2002). User interaction with building controls also changed with the development of more user-friendly graphical interfaces[36], such as readily-upgraded web-based interfaces with enhanced graphics, and the possibility of cost-effective control from remote locations (e.g., via the Internet). Clearly, building controls have changed dramatically since they were introduced into commercial buildings.

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[36] A survey of EMCS operators by Lowry (2002) found that operators placed less importance on the user interface, which Lowry believes suggests substantial improvement since the late 1980s.

EMCS interface with controlled devices in different ways. An EMCS with pneumatic communications has pressurized air lines that run from sensors[37] and controlled devices to the EMCS to indicate their state. Existing pneumatic sensors and controlled devices can communicate with a DDC-based EMCS by translating the pressure signal into a digital electronic signal (e.g., through a pressure-to-current converter) and using a computer to evaluate the system's state and decide on an appropriate control action. Another device translates the EMCS output signals into a pressure signal (e.g., using a current-to-pressure converter) and other pressurized air lines relay the control action to the controlled devices.

A DDC EMCS uses electronic signals to communicate digital information with controllers over a large area network (LAN), using either peer-to-peer or polling methodology. All controllers connected to a peer-to-peer LAN can communicate information directly with all other devices on the LAN, which facilitates the practical exchange of information between devices. In contrast, all controllers connected to a polling controller LAN send their information to an interface. The interface is connected to the peer-to-peer LAN and coordinates communication with other controllers or polling controllers connected to that peer-to-peer LAN. Polling controllers also may provide several other functions, e.g., data buffering. Some systems consist of a combination of both types of communication networks (see Figure 4-5; DDC Online 2003).

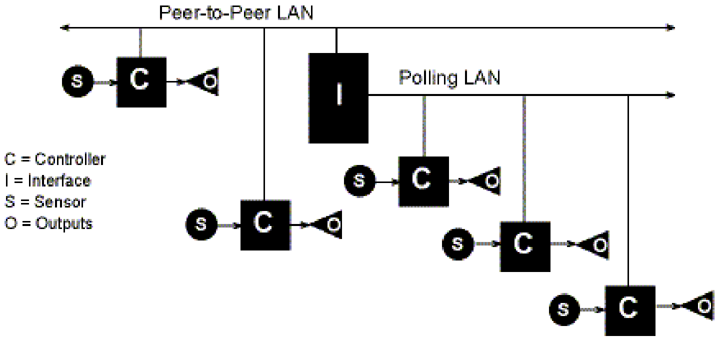

Figure 4-5: Schematic of a Peer-to-Peer and Polling LAN (from DDC Online 2003)

All EMCS have a centralized computer that interfaces with the communication networks. The computer provides the operator with the status of system components and provides higher-level (e.g., on-off, set point changes) control of systems. In the case of some larger EMCS, the requirements may exceed the capacity of a single LAN, which leads to the use of sub-networks (each with its own computer) that interface with a top-level network (DDC Online 2003).

EMCS have the potential to centralize a wide range of building control functionality because they can obtain information from numerous control points. Table 4-14 presents some of the EMCS capabilities deployed by a major retailer in their "big box" stores.

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[37] The air pressure reflects the state.

Table 4-14: Typical EMCS Capabilities of a Large Retail Establishment (based on Boler et al. 1997)

System	EMCS Capability
HVAC	• HVAC Start / stop and two stages of heating and cooling • Economizer damper status • Fan status • Discharge air temperature • Space temperature • Smoke and equipment alarms
Lighting	• Quadrant store lighting on/off control • Store lighting status • Display lighting control • Stock/receiving area lighting • Signs and exterior lighting • Employee parking lighting • Sunrise/sunset calculation
Miscellaneous	• Outdoor and indoor air temperatures and humidity measurements • Electric meter • Power condition (low voltage, phase loss) • Remote connectivity

Anecdotal information, however, suggests that building operators tend to use only a fraction of possible EMCS functionality, thus limiting the performance gains (Energy Design Resources 1998a; Ivanovich and Gustavson 1999; Hall 2001; Barwig et al. 2002, Lowry 2002). Surveys by Gordon and Haasl (1996) and Lowry (2002) can provide some insight into the general range of available EMCS functionality and the degree to which building operators exploit the available functions (see Figure 4-6 and Figure 4-7). Both surveys have limitations which raise caveats about the generality of the data (see Table 4-15).

Table 4-15: The Context of Building Surveys

Survey	Comments
Gordon and Haasl (1996)	• Mail-based survey coordinated with Building Owners and Management Association (BOMA) • 432 respondents • 71% of buildings had an EMCS • Provides data for usage of features • Focused on operations and maintenance practices • Primarily larger buildings – Mean building size = 230kft^2, Average building size = 347kft^2, 15 stories • Only office buildings • Higher-end Buildings: Class A – 67%, Class B – 30%[38] • Private management firms operate about 75% of buildings
Lowry (2002)	• 56 respondents • All buildings had an EMCS • Provides data for prevalence and usage of features • British buildings and service engineers • Respondents were building operators enrolled in a master's degree distance-learning course in building controls • All EMCS updated[39] in the prior 12 years, more than 70% updated in the prior two years

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[38] BOMA defines Class A buildings as: "Most prestigious buildings competing for premier office users with rents above average for the area. Buildings have high quality standard finishes, state of the art systems, exceptional accessibility and a definite market presence." Class B buildings are: "Buildings competing for a wide range of users with rents in the average range for the area. Building finishes are fair to good for the area and systems are adequate, but the building does not compete with Class A at the same price." Class C buildings are: Buildings competing for tenants requiring functional space at rents below the average for the area." From: http://www.boma.org/ProductsAndResearch/PropertyManagement/buildingclassification.htm .

[39] Updated refers to software and/or hardware upgrades to the EMCS.

The survey of Gordon and Haasl (1996) focused on larger, high-end buildings, which suggests that their findings have limited applicability to many buildings with less than 100,000ft^2 (and account for 78% of commercial building floorspace, per EIA 1999). Lowry (2002) relies on a small sample (56) of British building operators enrolled in a master's degree distance-learning course in building controls. In light of these concerns, the survey information should be viewed as providing a general, qualitative feel for the prevalence of EMCS functionality and their utilization.

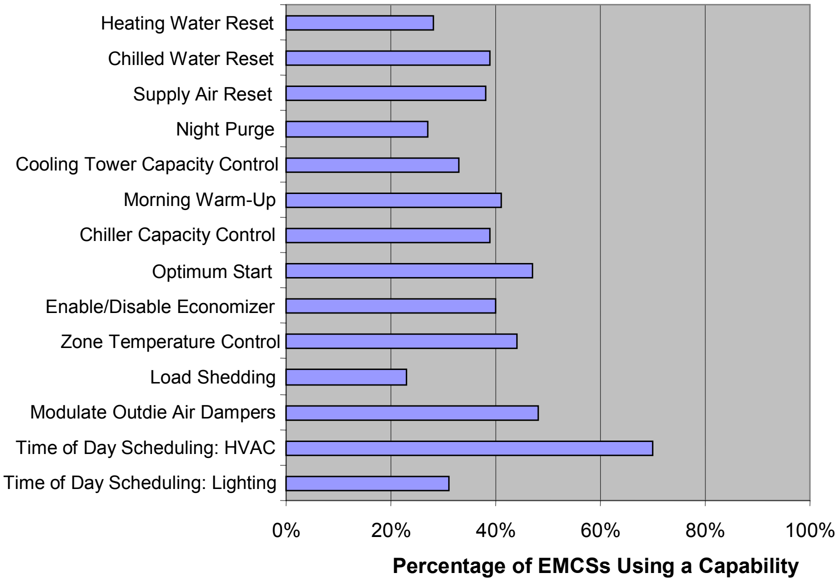

Figure 4-6: Use of EMCS Capabilities in Larger Office Buildings (from Gordon and Haasl 1996)

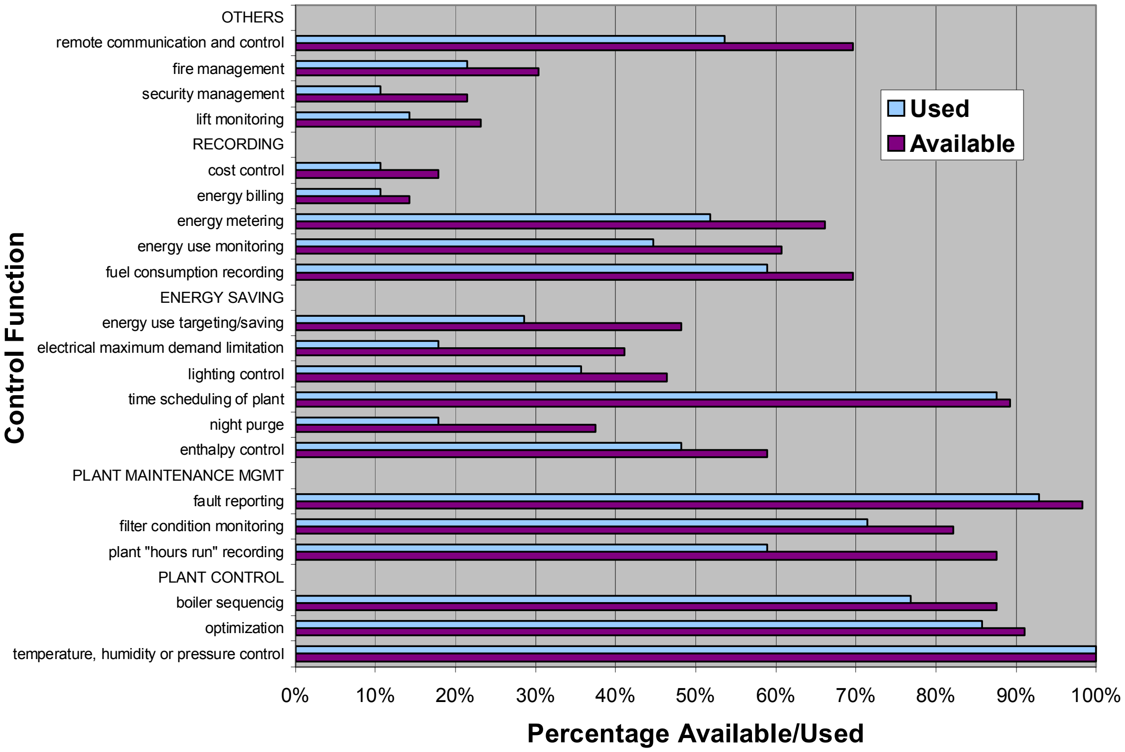

Figure 4-7: Surveyed Prevalence and Usage Rates for Selected EMCS Functions (from Lowry 2002)

Most EMCS have – and operators make use of – plant control and scheduling functions. In spite of the presumed bias that the populations considered in both surveys might have toward the use of more sophisticated functions, many operators only use a limited number of sophisticated functions such as night purge (pre-cooling), peak demand limiting, and temperature-based reset. That is, both surveys support the common supposition that many EMCS do not make use of a significant portion of their potential functionality and are "in many cases, just a sophisticated scheduling device" (Gordon and Haasl 1996). Furthermore, the relatively low levels of lift monitoring, security management and fire management functionality in Lowry (2002) suggest that most EMCS are not integrated with other building systems.

About 10% of the 4,650,000 commercial buildings in the U.S. have an EMCS. The probability of having an EMCS increases dramatically as the building floorspace increases; consequently, EMCS serve about 33% of the approximately 67 billion ft^2 of commercial floorspace (EIA 1999; see Figure 4-8).

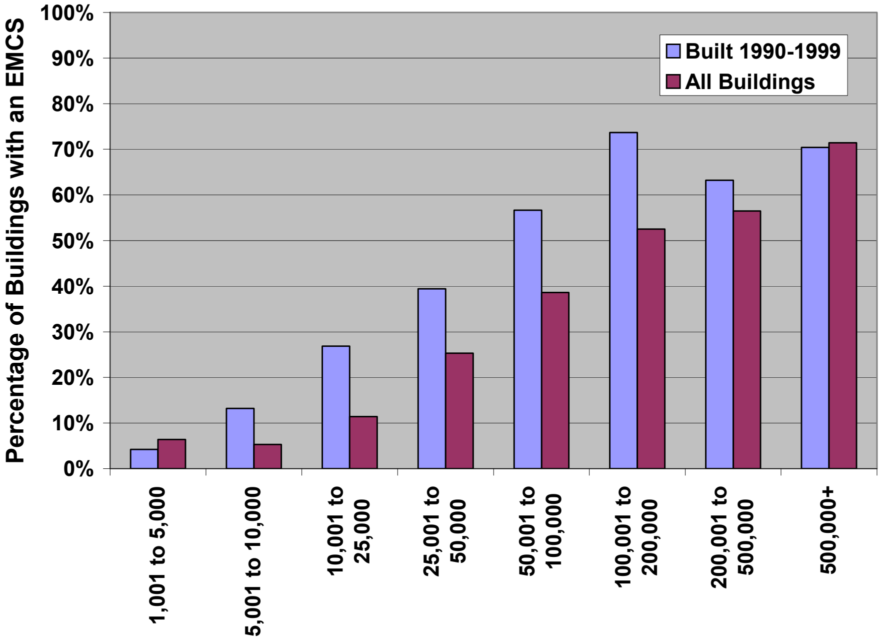

Figure 4-8: Percentage of Buildings with an EMCS, by Building Size Range (from EIA 1999)

The number of buildings with an EMCS increased from approximately 250,000 installations in 1995 (EIA 1995) to about 450,000 in 1999 (EIA 1999). The deployment of EMCS in new buildings, e.g., those built since 1990, appears to be responsible for much of the gain.

Several possible reasons exist for the 80% increase in EMCS installations, much of which has occurred in smaller new buildings. First, major building controls vendors recently have begun offering EMCS-like products[41] specifically targeted at light commercial buildings. These products offer much of typical EMCS functionality, such as remote access, multi-zone control, system monitoring, basic diagnostics, scheduling and setback, alarming, demand control, data logging and archiving, etc. Many of these products are designed for integration with and control of one or more packaged rooftop units, which are prevalent in light commercial buildings. Second, a general increase in the use of computers throughout society, accelerated by the rise of the commercial Internet, likely led to a greater computerization of building functions. Third, the functionality of building controls expanded and the user-friendly-ness of EMCS improved over this period while prices generally decreased, increasing the attractiveness of EMCS (BCS 2002). Key drivers included greater competition afforded by open protocols and continued decreases in the cost of computing power. Finally, facility management companies and energy service companies

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[41] See, for example, Trane's "Light Commercial Integrated Comfort^{TM} System" (http://www.trane.com/commercial/equipment/pdf/UNSLB002EN_r1.pdf), Honeywell's "Light Commercial Building Solution^{TM} (http://customer.honeywell.com/techlit/pdf/63-0000s/63-9094.pdf), and Andover Control's"onSITE^{tm}" (http://www.andoveronsite.com/Documentation/Brochures/onSiTE_Brochure.pdf).

(ESCOs) often install EMCS in buildings to monitor the building and quantify energy performance (Levermore 2000; Dreessen 2002). Recent trends indicate increased use of ECSOs (Reed et al. 2000; Dreessen 2002[42]), suggesting that they may have played a role in increasing the number of EMCS installations.

Figure 4-9 shows that EMCS have achieved the greatest market penetration (based on percentage of floorspace) in education and office buildings[43].

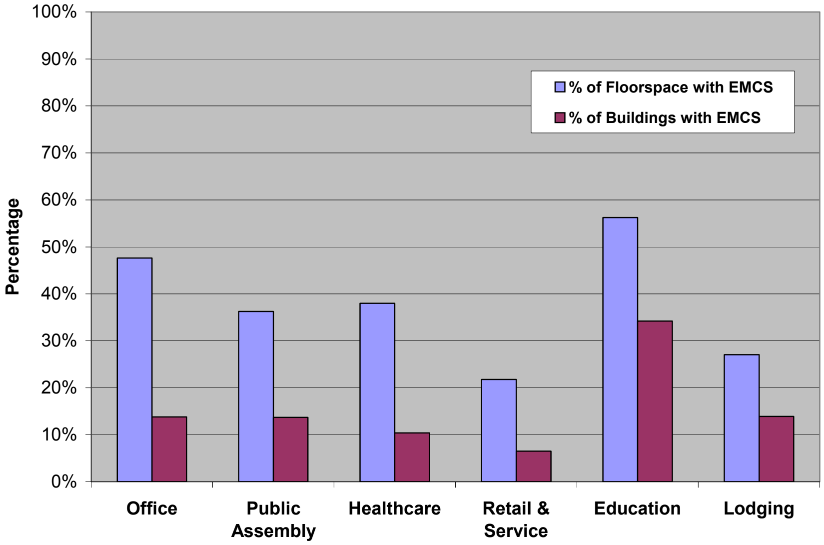

Figure 4-9: **Prevalence of EMCS by Building Type, by Percentage of Floorspace and Total Buildings (based on EIA 1999)**

EMCS also facilitate data monitoring and automate data collection and archiving while reducing data error and data logging labor. This information could be used to develop diagnostics for building systems and equipment (see Section 4.2). Future computerized maintenance management systems (CMMS) could also leverage data from EMCS to help develop responses to maintenance requests and prioritize activities (Piette et al. 2002; Federspiel and Villafana 2003).

4.4.1 Integrated Building Systems

At present, different building systems typically communicate information over different communication systems and do not share information between systems. Integrated building

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[42] Dressen (2002) reports that ESCO revenues from 1995 to 1998 approximately doubled relative to the preceding 4-year period. By footing the up-front expense of installing an EMCS, in exchange for a revenue stream over several years based on projected energy savings, the ESCO eliminates (from the owner's perspective) the first cost premium of the EMCS.

[43] Embedded in the health care data are hospitals, which also have higher-than-average percentage of floorspace and buildings served by an EMCS.

systems share information between systems and create the potential for increased data/information sharing and exchange between and from different sensors and building systems. In some cases, they may share the same communications infrastructure and operator interface. Table 4-16 presents the possible range of building systems integration, i.e., the degree to (and method by) which different building systems exchange information between each other, in order of increasing integration; "Electronic Communications between Controls in a System" is typical of most EMCS at present.

Table 4-16: General Range of Building Systems Integration, from Less to More Integrated (from BOMA 2000)

Integration	Description
Hard-Wired	Wired connection between controls
Electronic Communications between Controls in a System	Selected components of a common system communicate with each other; developed in proprietary controls/system context
Electronic Communications between Controls in Different Systems	Sharing of information between different buildings systems; around since mid-1990s
Building Systems Communicating with Management System	Front-end system integrates and shares inputs from different systems (potentially with different communication protocols)
Enterprise-Wide Electronic Sharing of Information Between Controls	Information potentially shared between most building system components

If building systems are integrated when installed, this can reduce the installed cost of the systems by sharing communications infrastructure, including media (e.g., wiring) and user interface. Integrated systems also can potentially reduce ongoing operator training costs (single versus multiple interfaces) and ongoing systems maintenance/updating (single infrastructure to support and single interface; CABA 2004b).

In addition, greater sharing of information from different systems may enhance the functionality of systems by taking into account a wider range of information about the entire building (see Table 4-17).

Table 4-17: Potential Functionality of Integrated Building Systems

Building System	Sample Functionality Provided to Other Systems
Access Control	• *HVAC, Lighting*: Turn on/off lights and alter space conditioning setpoints when people enter/leave building; provide feedback on actual building occupancy levels (e.g., to modify ventilation, estimate building loads) • *Security*: Alert operator when people access building at a given location • *Vertical Transport*: Activate/deactivate vertical transport when people enter/leave building
Fire / Life Safety	• *Access Control*: Alter building access/egress based on emergency status • *HVAC*: Modify ventilation in case of fire • *Lighting*: Activate lights in case of fire • *Security*: Communicate information to occupants in emergency situations • *Vertical Transport*: Disable or limit access in case of fire
HVAC	• *Fire / Life Safety*: Detect and communicate abnormally high temperatures
Lighting	• *Fire / Life Safety*: Communicate occupancy sensor status in case of fire emergency.

Building System	**Sample Functionality Provided to Other Systems**
	• *HVAC*: Communicate occupancy sensor status to modify local space conditioning setpoint • *Security*: Communicate occupancy sensor status in case of security breach
Security	• *Access Control*: Alter building access/egress based on security status or occupancy detection (e.g., from digital security camera; McGowan 2003) • *Fire /Life Safety*: Provide visual feedback on emergency events, e.g., locations of people and fire, intensity of fire
Vertical Transport	• *HVAC, Lighting*: Turn on/off lights and alter space conditioning setpoints when people access/leave portion of a building • *Security*: Communicate activity for CCTV monitoring

For example, a building with integrated systems could enhance the efficacy of a fire safety system by using CCTV feed from the security system to determine occupants' location. Specifically, integrated systems could share information to speed the evacuation of occupants, particularly those with disabilities. In addition, the building access system could enable or disable vertical transport systems as well as to turn on or off HVAC and lighting systems, e.g., when people arrive at work in the morning instead of at a pre-set time (McGowan 1995). Recently, web-based building systems have begun to come to market that facilitate information exchange not only between building systems but also with business processes. For example, a hospital with web-based communications and building systems can readily link patient status to room occupancy, i.e., to change the space conditioning set point and lighting based on occupancy. At the same time, the system can ensure that the room selected for a patient meets the specific needs of the patient, e.g., infectious disease isolation (Hill 2003).

The Building Owners and Managers Association (BOMA) carried out a survey that explored the degree to which building owners have and are considering applying systems integration (BOMA 2000). The survey found that:

- 50% of owners responding had invested in systems integration for at least some portion of their buildings;
- 75% had systems integration projects planned for "very near future",
- "Virtually all" firms who had made prior investments in building integration planned future projects involving building integration;
- In general, firms owning more buildings were more likely to have invested in building integration, and
- Cost was the primary driver in decisions to invest or not invest in systems integration, with reduced operating costs most important for those deciding to integrate systems and installed cost most important for those who decided not to pursue systems integration.

This clearly points out that building owners have an interest in integrating building systems if they feel confident that integrated building systems will provide real value, e.g., reduced operating costs. The same survey also found that building owners were most likely to integrate HVAC and fire safety systems on a building-wide scale first (see Table 4-18).

Table 4-18: Building Systems Most Likely to be Integrated First (from BOMA 2000)

System	%[44]
HVAC	91%
Fire Safety	77%
Electrical Monitoring / Management	50%
Access Control	45%
Power Consumption	45%
Life Safety	36%
Lighting Controls[45]	36%
Closed Circuit TV (CCTV)	27%
Lighting Management	27%
Vertical Transportation	18%

"Intelligent" buildings have received considerable attention due to their promise to reduce building energy, operations and maintenance expenses while improving the indoor environment. To achieve this, they typically deploy a wide range of sensors throughout the building, measuring temperature, CO_2, zone airflow, daylight levels, occupancy, etc. – that are integrated through an EMCS and an array of electronic actuators for VAV boxes, terminal unit controllers to process sensor outputs, and control airflow (CABA 2000[46]). However, many of these features have achieved negligible market penetration to date, e.g., the global market for IAQ sensors (including CO_2) did not exceed ten million dollars in 2001.

Furthermore, although these sensors can currently reduce building energy consumption via several controls approaches discussed in Section 9 (e.g., Demand-Controlled Ventilation, Optimal Whole Building Control, and Photosensor-based Lighting Control), it is not clear how integration of building systems will result in significant energy savings above and beyond those gained through the control of individual systems. That is, it is not clear that sharing information between fire safety, security, access control, lighting, and HVAC systems will further reduce HVAC energy consumption. Occupancy-driven approaches that could save energy, e.g., by adjusting space temperature setpoints based on a given worker's presence or absence, require HVAC systems capable of altering space setpoints at the scale of that worker's worskspace. Many buildings lack systems capable of climate control at that level of granularity. Although not part of most existing buildings, dynamically controlled shading systems are a notable exception, i.e., they require integration with daylighting control (photosensor-based dimming) and HVAC systems affected by the shading systems to realize their full energy savings potential.

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[44] Note that the percentages are not additive but represent the likelihood that an initial building integration effort would include that system.

[45] This parallels comments by a market manager of a large lighting control company commented that "integrating lighting with building automation is a fairly new technology. In the past …. It had to be done on a pretty custom, specific level" (Madsen 2001).

[46] CABA (2002) describes several "intelligent" building deployments and technologies.

In the future, building controls may require integration with and management of a wider range of building systems, such as on-site power generation (fuel cells, microturbines, photovoltaics, etc.), as well as the electric grid.

5 The Building Controls Market and How It Influences Building Controls Investments

The structure of both the building controls market and the greater market for buildings has a major affect on building controls purchasing decisions and, consequently, the opportunity for greater implementation of building controls to reduce energy consumption. The first section of this chapter, “Sales,” outlines the size and structure of the current building controls market and explains how this influences the market penetration of building controls. The second section, “Market Drivers for Existing Buildings,” describes how different building management paradigms impact investment decisions for existing buildings. Finally, the third section, “New Construction Practices,” discusses different construction paradigms and their influence on controls investments.

5.1 Sales

Table 5-1 summarizes the sales of building controls in the commercial buildings sector in 2001. In this context, BCS (2002) defines the term “building control systems” as “proprietary control systems platforms, related equipment and proprietary software”, including only DDC systems. Global annual sales are roughly three times greater than U.S. sales (BCS 2002).

Table 5-1: Annual U.S. Sales of Building Controls Equipment and Services (based on BCS 2002)

Category	Approximate U.S. Sales – 2001 [millions $US][47]
Building Control Systems	$340
Terminal Controllers[48]	$110
System Controllers[49]	$145
Network Devices[50]	$80
Instruments and Actuators	$400
Building Control System Installation[51]	$930
Application Engineering (Hardware configuration, schematics, software)	$240
System Installation, Wiring, Electrical	$525
System Start-Up	$90
Operator Training	$75
Building Control System Maintenance & Spare Parts	$1,175
Other	$70
TOTAL	$3,100

In addition, U.S. sales of dedicated lighting control systems and sensors, which include low-voltage switching systems and occupancy sensors, totaled about $80 million in 2001, with

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[47] Note: Imperfect sums reflect rounding.
[48] Unitary DDC controllers for zone, vent, VAV, etc.
[49] Rooftop, AHU, chiller, EMS, other multi-loop controllers
[50] Central workstations, application software (from BCS vendor), communications hardware, etc.
[51] Includes commissioning.

occupancy sensors probably accounting for at least half of this total. The global market for indoor air quality sensors (including CO_2), however, did not exceed ten million dollars in 2001 (BCS 2002).

The data presented in Table 5-1 reveal several interesting aspects of building controls. First, maintenance/spare part expenditures are much larger than purchases of building control systems and instruments and actuators, indicating the market importance of maintaining existing building controls. Second, system installation, including wiring and electrical work, account for more than half of the installation budget; indeed, installation and commissioning account for at least 70% of total installed cost (BCS 2002). Third, operator training accounts for a rather small – but not insignificant – portion of building control system expenses.

The "Big Three", Johnson Controls, Siemens Building Technologies, and Honeywell, account for about 50 percent of all building control system sales in 2001 (see Figure 5-1). Caffrey (2005) indicates that market shares and players have changes appreciable since 2001, notably due to corporate acquisitions.

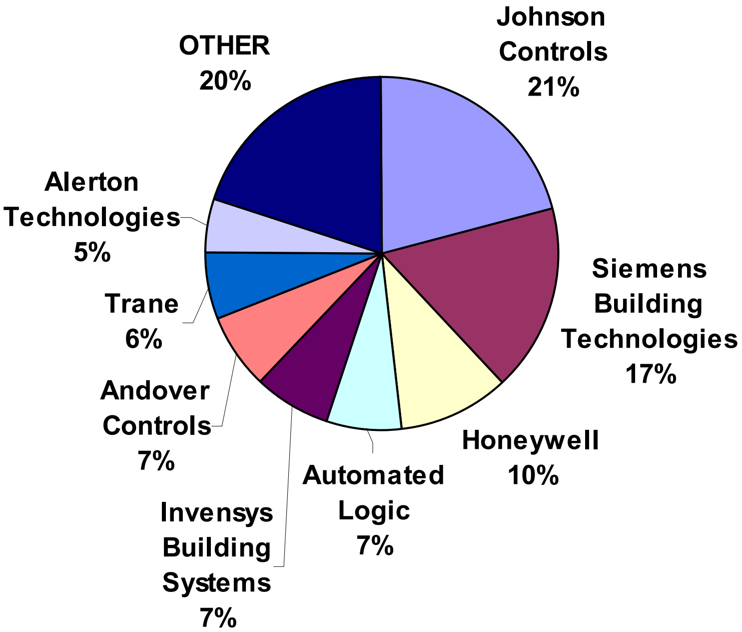

Figure 5-1: U.S. Building Control Sales by Company, in 2001 (based on BCS 2002)

Building controls products come to the end user through several different channels. Mechanical contractors account for approximately half, controls contractors one-third, and the branch offices of controls manufacturers one-sixth of building controls sales (BCS 2002). In some cases, a controls contractor purchases controls from a controls manufacturer and re-sell them to mechanical contractors. The mechanical contractor ultimately installs the controls.

Other commercial building systems, including fire protection and security (intrusion detection and automatic access control) and elevator monitoring, have a combined annual U.S. sales of approximately $2.5 billion (BCS 2002). Recently, the major building control companies have focused on providing a full range of building systems products, often acquiring fire protection and/or security businesses. For example, the “Big Three” all now offer a range of fire protection and security products

Office and commercial buildings (primarily mercantile/retail) account for about half of building control system annual expenditures, while office, industrial (conditioned space), and, to a lesser degree, educational buildings receive higher investment in controls on a $/ft^2 basis (BCS 2002). Existing buildings account for about 75 to 80% of new building control system installations and expenditures at present. This trend will likely continue for the next few years (BCS 2002). In the new construction market, EMCS installations closely track the volume of new construction and the education, government, and healthcare sectors represent the largest market segments.

Moderate growth of a couple percent per year is projected in dollar terms for most building control system products over the next several years excepting network devices, which project higher growth (approximately 5% compound annual growth rate). However, significant growth in unit sales will likely occur, as the cost per device continues to decrease for DDC equipment (BCS 2002).

5.2 Market Drivers for Existing Buildings

Building management and construction paradigms have a major impact on buildings decisions, including those related to building energy consumption (Reed et al. 2000). For existing buildings, the building management model has a dominant impact on who the key decision-makers are and what factors make different investment choices attractive. In the mid-1990s, owners occupied about 75%[52] of all commercial buildings (EIA 1999). Reed et al. (2000) notes that an overall trend exists for more occupants to lease buildings, because they desire greater flexibility to focus on core business concerns, i.e., they don’t want to acquire and manage property. They believe that the trend toward leasing will continue to increase in the future.

In existing buildings, decisions focus on building maintenance and renovation. The barriers to and value propositions for building control investments vary with the building ownership and operational model. Table 5-2 presents the four primary ownership models discussed by Reed et al. (2000) and a summary of how they tend to influence decisions related to energy

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[52] 74% of floorspace (EIA 1999).

efficiency. Much of the following discussion of different ownership and building management models paraphrases Reed et al. (2000)[53].

Table 5-2: Building Ownership Models and Impact on Building Controls Investments

Operating Model	Characteristics	Barriers to Building Controls	Value Proposition for Building Controls
Large Firms –Own, Operate & Lease Buildings	Regional or national scale firms, substantial staff at all levels	• Focus on maximum return on building (First-cost sensitive) • Tend to re-use prior designs	• Enhance attractiveness of leased space, i.e., perceived by tenants to enhance occupant comfort and productivity • Cost-effective measures that reduce maintenance also may succeed
Smaller Firms – Own, Operate & Lease Buildings	Local scale, less management structure, no planning/design staff	• Focus on maximum return on building (First-cost sensitive) • Lack of knowledge	• Short payback periods
Fee-Managed Properties	Property managers run property for owner	• Budget-driven process • Investment competes with core business (owner-users) or maximizing return on building (own-operate)	• Enhance market value of space • Maintenance and energy cost reductions with moderate payback period (<5)
Owner-Users	Focus on core business, general lack of information	• Investment competes with core business • Lack of information • Tend to re-use prior designs	• Proven measures with established short payback periods

Large Firms that Own and Operate Large Commercial Buildings lease and manage a large portfolio of commercial buildings on a regional or national level. Typically, they provide all building services throughout the entire life cycle of their buildings. Such large firms often have a complete range of corporate personnel responsible for different functions, including investment, operations, and maintenance mangers. Each building or building complex has a facility manager who assumes responsibility for operating and leasing that building or complex. They can formulate and make requests for investments, typically with a focus on reducing operations and maintenance expenses. Facility engineers and their staff actually operate and maintain the building.

The willingness of these firms to invest in efficiency measures depends on what the owner plans to do with the building (Reed et al. 2002). If they intend to *buy, renovate, and sell* the building, the firm will focus on measures that increase the selling price (and thus the lease rate) of the property. Efficiency measures that do not enhance a property's value need to recoup their cost within (or less than) the expected time before sale of the building, typically from a few months to three years. If, on the other hand, the owners plan to hold the building instead of selling, the investment horizon increases substantially, perhaps to as long as about five years (Reed et al. 2002). In the *buy/renovate/hold* case, several different parties impact investment decision in this model. Tenants can drive changes in the leased

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[53] This citation represents a synthesis of multiple studies carried out by the referenced authors and their associates, including numerous interviews and surveys of key parties in the buildings profession.

space that they want (the costs of which are recovered through the lease), and these tend to focus on reducing complaints from employees and improving employee comfort and/or productivity, e.g., layout modification and lighting. The building owner typically recovers his investment through the lease. When significant building changes are to be made, a centralized corporate design staff usually makes design recommendations and performs the design work, and consequently has a very large influence on design decisions. The design staff tends to be knowledgeable about energy issues, but their decisions, in turn, are shaped strongly by economic criteria (e.g., maximize building return) determined by investment managers (Reed et al. 2002; Diamond and Moezzi 2002).

Overall, building control measures that increase the attractiveness of the leased space, increasing rents, or that are perceived by tenants to enhance occupant comfort[54] and productivity have a superior chance of penetrating this market sector. Cost-effective measures that reduce maintenance also may succeed. In theory, energy efficiency investments can improve net operating income for properties and thus can increase property values (Innovest Strategic Advisors 2002). In practice, however, it is not clear that “green” building features such as building controls appreciably enhance the market value of buildings because most building appraisers[55] and lenders do not take into account building energy efficiency (Kozlowski 2003; DiLouie 2003c).

In contrast to the regional or national presence of larger firms, *smaller commercial owners* have less management structure and typically no planning or design staff. In this case, the owner and staff may work directly with facility managers in the management of the building in making facility decision. Reflecting a dearth of planning and design staff, this model places a heavy reliance on consultants or contracts with expertise to implement any design decision. Ultimately, the property owner usually decides the criteria for building investments, of which first cost usually ranks as the most important. As with larger commercial owners, the intentions of the property owner (i.e., to hold or sell) strongly influence the behavior of the owners. Owners who plant to hold the property may make investments with a short payback period (or those requested by a tenant). Smaller commercial properties generally have less access to quality information about energy-efficiency measures, reducing the likelihood that they will pursue sophisticated measures, e.g., integrated building systems.

In the *owner-user* model, a physical facilities manager takes responsibility for facility upgrades, maintenance, and operation. He ranks as the key decision-maker and makes his decisions within a budget-driven process, with a strong focus on reducing costs. Many owners occupy their buildings for the long-term and, because they pay for energy, they are willing to pay for lower-risk energy-saving investments with payback period as long as five

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[54] Preventing occupant *dis*comfort benefits the owner by increasing tenant retention; McGowan (1995) found informally through discussions with property managers that many tenants will began searching for new office space after their third space comfort-related complaint.

[55] A survey of 69 certified appraisers in California cited by DiLouie (2003) found that “only 13% recognized energy-efficiency features in their appraisals”, and that most assessments of operating costs do not explicitly include energy bills.

to seven years (Reed et al. 2002). In this environment, however, the owner's capital expenditures compete with corporate investments in the core business, which establishes another, often shorter, payback criterion for efficiency investments. Often, facility managers need to make decisions quickly and thus tend to go with proven designs used in the past. Consequently, owners tend to invest only in well-understood, mature building control (and energy-efficiency measures) with a proven quick payback. The dominant ownership model in the past, the percentage of owner-users has been declining as businesses focus on their core business and "farm" out facility management to property management firms or service contractors.

Property managers manage the commercial property for the owners in the *fee-managed property* model, providing a full spectrum of services including buildings operation and maintenance. A market research firm projects that integrated facilities management services will grow at a compound annual growth rate of more than 8% over the 2002 to 2009 period (ASHRAE 2003b). In this paradigm, the property service firm has a facility manager, combined with either in-building maintenance staff or roving maintenance staff, depending on the size of the building. The property service staff makes basic operational and maintenance decisions within the constraints of an agreed-upon budget. Although they often have contractual incentives to lower operating costs, this does not imply that energy saving is a high priority: "contracts are seldom written in ways that encourage the property manager to become an advocate for energy efficiency" (Reed et al. 2000). Larger capital investments involve owners owing to their financial scale. Typically, the property service company presents a range of potential projects to the owners with moderate simple payback periods (on the order of 3 to 5 years) and the owners select projects. Owners tend to favor investments that enhance the "rentability" and yield (rent) of the space, as well as those that achieve cost-effective reductions in operating expenses. Consequently, building owners are more likely to accept longer payback on building features that enhance building image. Overall, building control technologies that enhance the perceived market value of the property hold the greatest promise in this sector. Technologies that reduce maintenance and energy expenditures with a reasonable payback period (i.e., less than five years) can also prove attractive.

5.3 New Construction Practices

The new construction market would appear to offer more opportunities for energy efficiency measures and building controls because implementation occurs in a "blank slate" environment. In practice, the goals of the eventual building owner are not well-aligned with saving energy and limits the opportunities for building controls investments in new buildings. Table 5-3 shows the typical first cost structure of new buildings.

Table 5-3: Approximate First Costs for Building Systems in a Medium-Sized Office Building (from Dorgan 2000)

Building System	First or Operating Cost [\$/ft^2]
Building First Cost	$60
Environmental Systems First Cost*	$12
HVAC Systems First Cost**	$7
IAQ Support First Cost***[56]	$1
*Included in "Building First Cost" **Included in "Building" and "Environmental Systems" ***Included in "Building," "Environmental Systems," and "HVAC Systems"	

For buildings that will be let, the ultimate goal remains realizing the highest rate of return possible (Reed et al. 2000; Zimmer 2002). A senior VP for a property management firm indicates that this often focuses on short-term efforts to make more money, including (Brandeis 2003):

- Leasing more space;
- Increasing rents;
- Avoiding vacancies;
- Reducing operating expenses, and
- Improving debt to equity ratios.

Furthermore, tenants pay for energy (either directly or indirectly, via the lease) and, according to Reed et al. (2000), they typically care little about energy expenses: "energy efficiency is not usually an important leasing criterion for clients. Relative to other costs such as recruiting and retaining employees, lessees may find changes in energy costs quite marginal." Ultimately, the owner has little to no incentive to save energy because it is irrelevant to their business goals. In contrast, a more productive environment or one that projects a better image is of much greater interest to the lessee and to the degree this will command more rent, making those improvements will appeal to the lessor.

The dominant new construction process paradigms for commercial buildings tend to impede the effective deployment of building controls, particularly novel building control concepts such as integrated building systems. Table 5-4 shows an overview of the three models for new construction outlined by Reed et al. (2000); the bulk of the following paragraphs describing new construction models are based on Reed et al. (2000).

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[56] According to Dorgan (2004), typically includes items such as: outside air control, differential heating, cooling and dehumidification, humidity control in winter, either improved filtration or prefilters, related control costs.

Table 5-4: Models for New Construction (based on Reed et al. 2000)

Construction Model	Approximate Market Share	Characteristics	Barriers to Implementing Building Controls
Plan / Design / Build (or Design/Bid)	<~45%	• Architect integrates building construction process • Longer construction time than Design/Build	• Opportunities for more integrated controls approaches depend on architect
Design/Build	50%+	• Reliance on standard / pre-existing designs • Shorter construction time	• Little opportunity for integrated approaches • Avoidance of innovation
Collaborative	4-8%	• Systems approach used • Longer construction time than other paradigms	• Excellent opportunity for "whole buildings" approaches

Public, owner-occupied, and buildings with complex function often use the *Plan/Design/Build (or Design/Bid)* paradigm. In this model, the building owner selects an architect through a competitive process and the architect develops a detailed building design, often with help from specialist subcontractors. The architect then solicits bids from contractors to construct the building, chooses a contractor in conjunction with the owner, and then supervises and approves the construction. Thus, the owner and architect drive the process and make key decisions. The ability to implement more novel controls approaches, most notably integrated approaches, depends on – and varies greatly with – the ability of the architect to manage the different teams working on the building and successfully exchange information between them. Plan/design/build was once the primary model for new construction but the market has moved away from it and toward design/build due to cost and time constraints.

The *Design/Build* model centers on a building contractor selected by the building owner to design and then construct the building. To a large extent, the building design and construction are worked out independently of each other and in sequence. This approach fixes many design variables early on in the process, enabling different parts of the construction processes to overlap. Consequently, contractors tend to re-use structural elements from building to building (with some site-related variation) and design work is often formula and rule-of-thumb driven. While this approach expedites construction, it can constrain portions of the design decided later in the process significantly. Moreover, building controls are often the *last* aspect of building construction considered on a project, at which point in time funds usually are limited and contractors tend to select very basic and inexpensive building controls. All of these factors make whole building design and controls approaches very difficult to implement[57]. Presently, at least 50% of all new construction projects appear to follow the design/build model and its market share continues to grow.

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[57] For instance, fire protection system typically must be installed and fully operational before building occupancy (Brown 1998). If the HVAC system integrates with the fire protection system, it, too, must be completely installed before installation to demonstrate that it does not adversely impact fire protection system function.

In contrast to the other two paradigms, the *Collaborative* approach views a building as a system and strives to build a high-quality, well-integrated building. It takes a team-based approach to building design that involves the collaboration of team members throughout the design and construction practice to effectively consider and exploit interactions between different building systems (e.g., via modeling techniques). For example, a decision on how to design a large atrium might include discussions between architects (overall building perspective), HVAC contractors (HVAC system design and cost, building loads), a lighting consultant (lighting impact, including daylighting), structural engineer (how to implement), and a space designer (how to use the space). Consequently, the collaborative approach requires extensive and active communication and sharing of information between all of the parties involved in the building process. Because it takes a whole building view of the building, the collaborative model has a large potential for achieving energy efficiency, including the use of sophisticated controls and integrated building systems. Due to the need for extensive up-front design integration and continued information sharing, the collaborative model typically has a higher first cost and takes longer to construct than design/build and plan/design/build. This makes it unattractive to many building owners, who want to realize a return on their investment as quickly as possible. Currently, approximately 4 to 8% of commercial building projects use the collaborative approach.

Clearly, the collaborative model offers the most opportunities for deploying sophisticated building controls in new buildings. A comparison of the design/build and plan/design/build with the collaborative process reveals major differences between the paradigms. Bridging these differences to implement integrated building systems in a larger percentage of the national building stock will require many changes in current building practice, as many roles that are currently clear-cut become blurred from system integration (see Table 5-5).

Table 5-5: Issues Arising from Differences Between Current Building Practice and Integrated Building Systems

Typical Current Practice	Integrated Building Systems	Issues
Building systems have separate communications systems	Common communication systems	• Who is responsible for making system work, particularly at subsystem interfaces? • Who is liable for system failure? • Who maintains common system?
Building systems installed, function and maintained independently	Building systems integrated	• Who assumes liability for construction risks (costs, delays, etc.)? • How to troubleshoot / commission a much more complex, integrated system? • Who maintains system components? • Who can access common system infrastructure? • Who is liable for system and component failure?

Presently, many controls contractors tend to specialize in one type of building system and different contractors handle different building systems. For example, most building projects use a single HVAC controls contractor to install the building controls and who often sells the products of a single controls equipment manufacturer. The controls contractor selects the controls equipment and programmed the controls such that they meet the operational requirements incorporated into the project specifications. As the project evolves, the controls contractor supplies control hardware (dampers, valves, etc.) to the mechanical contractor for installation, while also providing control equipment to equipment manufacturers for factory installation prior to shipment to the field. Hartman (2000) notes that:

> the extensive digital controls packages supplied by chiller, boiler and fire alarm manufacturers are largely ignored by the HVAC controls contractors who generally install a few discrete control and/or monitor points to transfer essential information between the systems while ignoring the valuable factory installed instrumentation and logic capabilities.

Near the end of the project, the controls contractor installs additional control devices and controllers and makes the necessary connections to complete the physical control system. At the same time, the contractor programs (for DDC) the control logic needed to realize the specified sequence of operations, typically using a control manufacturer's canned application programs. The control specifications, however, often were developed without knowledge of the controlled equipment and the full intent of the control sequences, which compromises control effectiveness. In sum, this process is prone to higher cost (single vendor), decreased controls efficacy, and can cause construction delays due to problems integrating controls into equipment (Hartman 2000).

Overall, a limited number contractors can carry out a project requiring widespread system integration due to lack of knowledge or capability of how to achieve effective system integration combined with little – if any – experience in implementing integrated building systems (Ivanovich and Gustavson 1999; BCS 2002). Instead, larger numbers of systems integrators need to arise to take responsibility for and manage control systems integration process from design conception through building commissioning. Indeed, building controls industry analysts expect that the systems integrator will become the key player in the building controls market over the coming decade (Hartman 2000; BCS 2002). To some extent, that has begun to occur as the result of mergers in both the building consulting and contracting industries (Mellor 2003). Both trends should increase the range of services offered by consultants and contractors, as well as their geographical reach. Thus, consulting firms have greater familiarity with different building systems, increasing the likelihood of specifying integrated building systems. Similarly, some major contractors can now install multiple kinds of building systems, which increases their ability to successfully implement integrated systems.

Recent decisions to modify the organization of the building construction process to include communications could enhance the potential to consider and deploy more sophisticated controls approaches and integrate building systems. The current MasterFormat^{TM} specification consists of 16 Divisions that organize "information about construction requirements, products, and activities into a standard sequence" for commercial buildings"

(CSI 2002). Many parties have pushed for creation of a new Division to address telecommunications and networking to reflect changes in these areas since the last MasterFormat^{TM} update in 1995. Typical design practice does not consider telecommunications and networking needs until very late in the construction process, i.e., when funds tend to be scarce and most of the building infrastructure has been already specified. This practice poses barriers to consideration and implementation of integrated building systems, as low-cost systems are often “shoe-horned” into the existing infrastructure, creating a sub-optimal installation (Thomas 2001). Creation of a new Division would integrate telecommunications and network design into the up-front building design and planning process. In 2002, the board of the Construction Specifications Institute (CSI - the organization that maintains and amends the MasterFormat^{TM}) voted to create three new divisions to the MasterFormat^{TM} for communications, electronics safety and security, and integrated automation[58] (Jannicelli 2003). The creation of clear divisions for all three areas should facilitate the consideration and design of integrated building systems.

Looking forward, the development of truly integrated building systems will place a high value of ensuring the reliability and robustness of building communications, whatever medium and protocol is used. The integration of communications for all building systems into a single infrastructure increases the need for reliable communications and systems. Whereas a failure in one communication system in conventional practice remains isolated to that system, the failure of an integrated building communication system could potentially bring down the entire system. Survey results reported by Lowry (2002) indicate that EMCS reliability ranks as the most important general system attribute, and that most users are quite satisfied with current system reliability. It will be crucial to ensure that communications have sufficient reliability, resiliency, and redundancy to avoid failures.

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[58] A draft of the proposed new CSI MasterFormat^{TM} can be viewed at: http://www.csinet.org/s_csi/docs/7400/7379.pdf .

6 Barriers to Building Control Systems and Diagnostics

Several barriers exist to the deployment of building controls, particularly sophisticated building controls. Chapter 5 discusses how building management and construction paradigms affect building controls investments and this chapter focuses on other barriers to building controls. Cost, specifically first cost, poses the greatest barrier to increased use of building controls. Many owners simply refuse to pay more for a system, while others may not believe that building controls offer an attractive simple payback period. In addition, a general lack of knowledge about building controls at many levels impairs effective decisions and implementation. Subpar implementation, in turn, often leads to under-performance of building controls, which decreases the credibility of controls measures in the eyes of decision makers. Continued problems with interoperability of building controls products from different vendors decrease competition for the provision of all hardware and services; this increases the first and ongoing costs of building control systems.

6.1 Cost Barriers

A central issue with all energy savings measures is that energy costs simply do not represent a significant portion of expenditures for most buildings and buildings owners and tenants typically care little about energy expenditures. For instance, one study found that energy expenditures account for just over 1% of *total* annual expenditures for a medium-sized office building (see Table 6-1).

Table 6-1: Breakdown of Typical Small Office Building Annual Expenditures (from Cler et al. 1997)

Expenditure	Annual Cost [\$/ft^2]
Office-Workers' Salaries	130
Gross Office Rent	21
Total Energy Use	1.81[59]
Electricity Use	1.53
Repair and Maintenance	1.37
Space Cooling and Air Handling Electricity	0.61[60]
Space Cooling and Air Handling Maintenance	0.82
Total Building Operations and Management Salaries	0.58

On average, energy accounts for about 30% of private sector commercial office building operating expenses (see Figure 6-1, based on BOMA 2001).

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[59] Dougan and Damiano (2003) note a range of \$1.00 to \$2.00/ft^2 for office buildings. DiLouie (2003) states an average of \$1.06/ft^2 for *all* commercial buildings, which includes unlit floorspace equal to ~12 billion ft^2 out of a total of ~67 billion ft^2 (EIA 1999).

[60] From TIAX (2002).

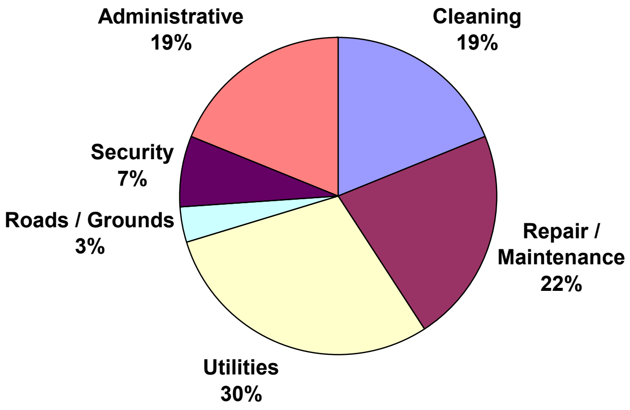

Figure 6-1: Average Operating Expenses for Rented Private Sector Office Buildings (based on BOMA 2001)

Energy expenses may equal a higher percentage of building operating expenses in other kinds of buildings, such as retail or food sales. In those cases, energy efficiency measures compete directly with investments in core business functions, e.g., enhanced lighting or displays that can increase sales of clothes or food. Consequently, building owners and/or operators need to have very high levels of confidence that building controls investments will have a very quick payback to prove attractive. Institutional parties such as governments, schools, and some hospitals, may accept somewhat longer (up to around 5 years) simple payback periods.

Typically, HVAC equipment and system controls minimize the number of sensors used in an effort to achieve low first costs (VTT 2001). Recent data for EMCS installations suggest that each point (control and monitoring) has an average installed cost of about $600 (Xenergy and Nexant 2002). Table 6-2 provides information about the approximate installed cost of different sensors and control points for centralized building controls. In many cases, labor accounts for a much larger portion of installed cost than the sensor, notably with the most common sensor type, temperature sensors. All of the costs include conduit electric metallic tubic installation of the wiring, with the exception of the space temperature sensors (which use plenum cable instead). As Caffrey (2005) notes, this significantly increases labor costs relative to simpler low-voltage wiring installations. Similarly, some applications, e.g., factory-installed sensors used in equipment, can use sensors with simpler packaging that cost much less than the values shown in Table 6-2 (see Section 9.5). Additional costs accrue to purchase an EMCS and integrate the different control points into the EMCS (see Table 6-3).

Table 6-2: Typical Costs for EMCS End Devices (Based on RS Means, from Xenergy and Nexant 2002)

Monitoring Point	End Device	Material [$]	Labor [$]	Total [$]
Outdoor Air Temperature	RTD with enclosure	40	600	640
Space Temperature	RTD (wall-mounted)	30	600	630
Exhaust Air Temperature	RTD (duct-mounted)	65	325	390
Chilled Water Temperature	RTD (brass well)	90	850	940
Duct Static Pressure	Differential Pressure Sensor	275	325	600
Fan Status	Current Sensor	100	480	580
Electric Consumption	Electric Meter	1,150	500	1,650
Water Consumption	4-inch Water Meter	1,650	650	2,300
CO_2 Level	Duct Mount CO_2 Sensor	800	425	1,225
Control Points	**Description**	**Material [$]**	**Labor [$]**	**Total [$]**
Chilled Water Valve Control	3-inch two-way valve with electric actuator	530	550	1,080
Mixed Air Damper Control	Two electric damper actuators, proportional with spring return	960	500	1,460
Fan Speed	Variable frequency drive input	125	325	450
Pump Start/Stop	Low Voltage Relay	35	595	630

Table 6-3: Additional Material and Implementation Costs (250-point System; based on RS Means, from Xenergy and Nexant 2002)

Hardware and Software System Components	Description	Material [$]	Labor [$]	Total [$]
EMCS Workstation and Peripherals[61]	Workstation and peripherals	6,000	250	6,250
Central Computer EMCS Software	Functionality includes: remote monitoring, control, control strategies	6,000	0	6,000
EMCS Communications Network	2,000 feet of plenum cable	3,000	4,000	7,000
[13] 16-point Control Panels		2,000 each	300 each	29,000
[4] 32-point Control Panels		3,500 each	550 each	16,200
System Design and Installation	**Description**	**Material [$]**	**Labor [$]**	**Total [$]**
Calibration	Analog Point Calibration		80 / point	20,000
System Commissioning	End-to-end wiring check, end devices operation, program installation and verification		120 / point	30,000
System Engineering	System design and point programming		80 / point	20,000
Project Management	136 hours		120 / hour	16,320
			TOTAL	151,670

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[61] Listed as "Outside Air Temperature" in Xenergy and Nexant (2002), but description clearly alludes to a workstation and components for an EMCS.

Overall, EMCS implementation costs equal roughly $600 per point, increasing the per-point total cost to $1,200 (Xenergy and Nexant 2002). As noted earlier, installations that did not require conduit for controls wiring would have appreciably lower labor costs (Caffrey 2005) and somewhat decrease the overall per-point cost. Effective implementation of sophisticated controls and diagnostics often requires several additional sensors (relative to more basic controls) to obtain the necessary data to develop accurate diagnoses. The need to purchase, install, and commission additional sensors increases the system's cost significantly and impedes deployment of controls and diagnostics. As noted earlier, installation and commissioning account for at least 70% of the installed cost of centralized building controls (BCS 2002). Measures that significantly reduce the *installed* cost of building controls can increase their market attractiveness and, presumably, penetration.

A lack of building operator time to address building energy issues represents, in essence, another cost barrier to building controls, particularly sophisticated controls. In most instances, building operators and facility managers have numerous responsibilities beyond managing building energy consumption. This limits the amount of time (in essence, money) that they can spend monitoring – let alone improving – building operations. In the case of EMCS-based building diagnostics, successful installation and configuration of diagnostic tools and understanding diagnostics tools can consume much time. Many building operators cannot invest the time needed to overcome the initial learning curve associated with the diagnostic tools, impeding their effective exploitation (Friedman and Piette 2001). Similarly, regular day-to-day demands on the building operator's time can prevent operators from considering diagnostics' output. Actually resolving problems identified by the diagnostics can prove challenging. Diagnostics do not, per se, save energy but provide the opportunity to save energy by addressing subpar equipment or system performance. In many instances, building operators lack the resources (time, personnel or funds) needed to confirm the problem and then fix it (Friedman and Piette 2001). For example, very limited field testing of a diagnostic tool for outdoor air economizers found that the tool users usually did not implement the diagnosed faults because they were too busy or lacked authority to order the repairs (Architectural Energy 2003).

The first cost of an EMCS and EMCS management (personnel) costs inhibits the deployment of EMCS in smaller buildings. As shown in Figure 4-8 (see Section 4.4), the likelihood of having an EMCS installed correlates strongly with building floorspace. Although some portions of an EMCS, notably communications infrastructure and control points, may roughly scale linearly with square footage, the basic centralized portion of the system does not. EMCS of any size also require a basic level of human oversight to function properly and smaller facilities may not be able to afford the trained staff required to operate the EMCS. Both factors tend to increase the installed and operating costs on a $/ft^2 basis of EMCS in smaller buildings relative to larger buildings, which increases their attractiveness in larger buildings. In addition, smaller buildings usually have fewer zones and to require less sophisticated control than larger buildings and may not reap the same energy and maintenance benefits from the centralized control. Instead, most buildings without an EMCS have very basic building controls, i.e., thermostats (with setback capability) to control air temperature in the different building zone(s).

Many building controls approaches tend to not have well-defined energy saving and payback periods. The financial uncertainty (and, hence, risk) involved with applying these controls measures makes designers less willing to consider the approaches and negatively affects their market potential. Occupancy- and photosensor-based lighting controls illustrate this point. The costs and benefits of occupancy sensors depend on room layout (which affects ease of commissioning), controlled lighting power, and occupancy patterns. Consequently, occupancy sensor energy savings claims lie between 20% and 70% of lighting energy for individual spaces (Energy Design Resources 2000; VonNeida et al. 2000; Jennings et al. 2000; EIA 2001) and installed costs vary greatly. Spaces with sporadic occupation patterns have higher energy savings potential, such as private offices, classrooms, auditoriums, restrooms, and conference rooms (Energy Design Resources 2000). Public spaces with almost continuous occupancy have little potential for saving energy, e.g., common hallways, lobbies, or open-plan office spaces. Photosensors for lamp dimming in response to daylight and/or over-lamping appear to have even greater cost variability, due to high uncertainty in installation labor (for wiring and commissioning). PG&E (2000) interviewed various contractors and established a broad installed cost range of approximately \$0.20-\$3.00/ft^2.

Building owners also view novel building controls as carrying greater financial risk than conventional controls measures, due to their relative immaturity, poorly understood cost structure, and a general skepticism about purported cost savings. As the “Technology Roadmap for Intelligent Buildings” prepared by the Continental Automated Buildings Association found, most intelligent building projects lacked full instrumentation and documentation. This prevents meaningful quantification of the costs and benefits of “intelligent” buildings (CABA 2002a). Establishing a meaningful cost-benefit relationship between novel building controls – such as integrated building systems – is a vital part of gaining building owner confidence so that novel building controls can achieve significant market penetration (Ivanovich and Gustavson 1999).

New integrated or “smart” buildings also generally cost more to build due to greater system integration and the need for more control and measurement points. Incorporating building integration into existing buildings is particularly challenging because it requires installation of the sensor and communications infrastructure on top of existing building systems. This can prove “quite prohibitive”. Replacing existing pneumatic controls with DDC systems “can add exorbitant cost.” Similarly, the cost of integrating separate building systems into a single EMCS “can be quite high due to the need for communication gateways and revised software” (Energy Design Resources 2001). Unsurprisingly, a survey carried out by BOMA (2000) revealed that cost dominates decisions not to invest in systems integration (see Table 6-4).

Table 6-4: Top Five Reasons Building Owners Do Not Implement Building Systems Integration (from BOMA 2000)

Reason
1. High Installation Cost
2. Lack of Cost Justification
3. High Systems Integration Cost
4. Lack of Funding
5. Lack of Awareness[62]

6.2 Knowledge of Controls

A relatively low level of understanding of building controls and systems by all parties involved, ranging from building owners to system designers and building operators, results in subpar building controls selection, implementation, and performance. The rapid evolution of the building controls from mechanical to digital and their increasing complexity are overarching challenges that exacerbate a general lack of knowledge. Table 6-5 summarizes how relevant parties suffer from understanding gaps specific to their position and how this adversely impacts the energy efficacy of building controls.

Table 6-5: Impact of Understanding Gaps of Key Control Parties on Building Controls Energy Performance Shortfall (based on Barwig et al. 2002 and other sources)

Party	Understanding Gap	Reason for Energy Performance Shortfall
Building Owners	Pros and cons of different control systems, components	Purchasing decisions based on first cost (minimal product differentiation)
Control System Designers	Impact of control strategies on energy consumption	Energy-efficient control strategies not considered and specified
Control System Specifiers	Optimal sensor placement	Sensors cannot provide most useful / appropriate information to EMCS
EMCS Operators	Control procedure intent / EMCS operation	Limited repertoire of operating procedures leading to inadvertent energy waste

The general lack of knowledge of building controls clearly manifests itself during the development of EMCS specifications, which often are not application-appropriate and result in selection of an inappropriate system (Santos and Brightbill 2002; Hartman 2000). Inadequate EMCS specifications also adversely affect system interoperability. For example, Santos and Brightbill (2002) note that many systems are not specified to the level needed for the context, i.e., simply demanding adherence to an open protocol does not result in an interoperable systems. In other cases, controls specifications may call for outdated products, omit control point locations, or omit key control points (Keithly 1997). Furthermore, many control systems lack full documentation of the system in its operational context, i.e., such that the operator has sufficient explanation of design intent to understand the system and all information needed to maintain (i.e., re-program as needed) the system (Santos and Brightbill 2002; Keithly 1997; Gordon and Haasl 1996).

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[62] Presumably, of the benefits of building system integration.

Section 6.1 notes how many building operators and facility managers have little time to monitor or improve building operations, or to learn more about building controls or diagnostics. Surveys of building operators by Gordon and Haasl (1996) and Lowry (2002) provide additional insight. Most building operators appear to receive very little training, i.e., Gordon and Haasl (1996) reported that more than half the building operators had an annual training budget of under $500 and Lowry (2002) found that more than half of the EMCS operators surveyed had had three days or less of training. When building operators did receive training, it typically was to satisfy certification requirements, learn to how operate new equipment, or in response to a staff member's request for training (Gordon and Haasl 1996). However, Lowry found no meaningful correlation between operator training and utilization of EMCS features. The survey also revealed that operators were satisfied with most EMCS functions, but showed somewhat lower satisfaction with data recording and plant maintenance functions. On the other hand, EMCS operators expressed some dissatisfaction with the EMCS commissioning process, which endured an average of 9 months. Software problems accounted for about half of issues, while the performance of the commissioning agent ranked as the next largest problem.

The general nature of the buildings controls industry also works against full exploitation of the potential of building controls. As noted earlier, building controls have evolved greatly over the past couple of decades, with major changes in all facets of the business. Even as building controls have progressed from mechanical to digital, most HVAC engineers, designers, and technicians still have a mechanical background (Sellers 2003a). This likely plays a major role in properly configuring and installing controls. Similarly, it impedes effective diagnosis of control problems, e.g., a manager of a major packaged RTU manufacturer estimates that approximately 30% of "failed" controls actually work fine (Lord 2005). Keeping up with the changes – let alone advantage of – the new opportunities they afford – requires talented workers. An executive in the fire protection industry argues that the current industry structure does not support the employment of such personnel:

> "modern building systems are computer systems, and the vendors are competing with all other aspects of the information technology industries for qualified technicians. These technicians are expected to know the hardware and software of the control system, as well as all relevant codes, standards and industry practices related to HVAC control, fire alarms, elevator control, security, lighting control, etc. This is an unreasonable expectation considering industry pay scales, training, turnover and service call charge rates" (Brown 1998).

This parallels long-running complaints from the HVAC industry about the difficulty of finding qualified, good technicians.

In general, information about building controls needs to be more accessible and usable for various purposes, i.e., different levels of information for different users of information. For example, property managers desire building controls information translated into financial terms that address their primary goal of making more money from a property, e.g., how would a given building controls investment increase rents or improve tenant retention (Brandeis 2003; Zimmer 2002).

6.3 Under-Performance of Building Controls

Success in the field is very important to establish the credibility and value of energy efficiency measures, including building controls. If a building controls approach falls substantially short of promised energy savings levels, the resulting credibility gap inhibits further deployment of the approach.

Numerous studies suggest that a substantial portion of building controls at *all* levels do not realize most of their energy-savings potential. In many instances, problems with building controls arise soon after their installation, likely due to improper installation that is not identified during system commissioning. Other control problems arise after commissioning, apparently due to operator modification of control parameters (Potter et al. 2002; Ardehali and Smith 2001). Unless the control problems affect occupant comfort, they often remain undetected. Section 8, "The National Energy Impact of Building Equipment and System Faults," discusses building faults, including controls-related faults, in greater detail. Commissioning of new buildings can identify a wide range of control faults; however, new commercial building commissioning rates are less than 5%[63] (Dodds et al. 1998). Retrocommissioning usually uncovers controls problems in existing building but it is quite rare, i.e., only about 0.03% of existing buildings are commissioned in a given year (Dodds et al. 1998).

A lack of awareness of commissioning and the cost of commissioning appear to bear responsibility for low commissioning rates (RLW Analytics 1999). Twenty or thirty years ago, the installation of new building systems used to include commissioning. As building systems pressures to reduce costs increased, commissioning became a separate, optional service despite the trend toward more complex systems that have a greater need for commissioning (Nolfo 1997).

6.4 Interoperability

Despite the development of open communications protocols for building controls, most controls made by different manufacturers[64] appear to not be interoperable, i.e., they cannot readily communicate essential control information directly with each other. This poses particular difficulties, in upgrading many control systems or integrating separate building systems into a single EMCS, which require middleware to translate information between devices. Challenges in sharing information also hamper the implementation of add-on software tools to improve building function, such as diagnostic tools and energy information systems. Truly interoperable building controls will increase competition for the provision of all hardware and services and reduce the first and ongoing costs of building

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[63] Public buildings appear to have significantly higher commissioning rates due to mandates and/or practice (RLW 1999; Quantum 2003).

[64] And, in some cases, different products made by the same manufacturer.

control systems. Interoperability should also provide access to a wider range of functionality because it facilitates data sharing with other applications and processes.

Section 4.3.1 discusses the challenges facing building controls interoperability and potential solutions in greater detail.

6.5 Codes

Conflicts with or ambiguity about building codes and standards may impede the deployment of novel building control systems. In particular, fire codes appear to pose a significant barrier to full integration of building systems. Fire and life safety systems can include many sensors and be quite sophisticated e.g., some incorporate automated response sequences when a fire occurs (annunciation of fire, smoke pressurization). More advanced systems multiplex data from different fire zones to provide more detailed data that help to fight the fires and evacuate occupants. Because they are responsible for protecting the building occupants from fires, fire protection systems need to have a very high degree of reliability and integrity to ensure function in emergency situations, even when other systems fail. Consequently, they require isolation from potential interference from other building systems; fire systems can provide information to – but cannot receive information from – other building systems, limiting integration possibilities. In addition, the National Electrical Code requires that conductors remain separate from communication and power circuits to prevent interference (Brown 1998). In principle, any building control system that meets the requirements of NFPA 72, it can serve as a fire system (McGowan 1995). The controls must comply with UL 864 "The Standard for Fire Alarm System Control Units". In turn, UL 864 requires (among other things) that microprocessor-based fire alarm systems store control logic in nonvolatile memory (Brown 1998) and backup power and power-transfer safeguards (Vaughn 2003). This adds complexity, and increases the required reliability[65] and system testing, all of which increases the cost of integrating an EMCS and fire system control into a single interface in existing buildings (Turpin 2005a). The Uniform Building Code also specifies maximum damper and fan response times (Cardenal and Prowse 2001). Building equipment used for building control and smoke management functions, such as a variable-speed drive, must be designed to maintain the equipment's smoke management settings, e.g., in case of a power outage or from manual re-configuring of control parameters (Vaughn 2003). According to Bushby (2001), proper system design practice should be able to overcome the integrity concerns to enable greater integration. In practice, however, the fire protection industry is slow to change and unlikely to rapidly adopt new technologies and/or practices (Phillips 2003).

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[65] This includes communication network reliability. Turpin (2005b) notes that enterprise networks may not have the necessary back-up power to ensure continued fire system functionality in the case of a power outage.

7 Drivers for Building Control Systems and Diagnostics

Initially, EMCS were installed to reduce operations and maintenance costs. When energy prices skyrocketed during the 1970s, reducing energy costs became a valuable function. Nonetheless, maintaining occupant comfort ranks as the foremost goal of buildings operations. Indeed, a survey of EMCS operators found that the overwhelming majority – 48 out of 58 respondents queried – cited "control of comfort" as their primary objective[66] (Lowry 2002). This coincides with the findings of a survey of office tenants by BOMA (1999) that 99% percent of respondents rated "comfortable temperature" and "indoor air quality" as the most important building features. A more recent survey by the International Facility Management Association of its members found the same result (ASHRAE 2003c). Tenants expressed limited satisfaction with the ability of their current building to achieve these characteristics, with satisfaction rates of 74% and 81%, respectively. Clearly, this also impacts tenant retention (McGowan 1995). On the other hand, only one operator rated "Cost Saving" as the top requirement. Consequently, enhancing occupant comfort[67] and productivity ranks as the primary value proposition for controls, with cost-effective reductions of operating and maintenance expenses as a second potential proposition.

7.1 Enhanced Indoor Environment

The dominance of worker salaries in an office setting (see Table 6-1) suggests that building controls investments that enhance the productivity of workers, even by only 1% or 2%, would be very attractive investments[68]. Many lighting professionals see this as a key driver for greater installation of lighting controls (see, for example, LRC 1998, Jones and Gordon 2004, the Light Right consortium[69]). Similarly, a building EMCS that results in a more enjoyable working environment may reap significant value by increasing employee retention. In retail or food service settings, if building controls can improve the indoor environment and increase sales by a relatively small percentage, they would make an attractive investment for those applications. In all cases, **building controls can greatly increase their value by enhancing the core business of the building – be it office employee productivity or increased sales**. All parties benefit from a more productive environment. The building occupants realize the aforementioned gains and the lessor can differentiate his property and command greater rents.

Prior research suggests a general, positive relationship between occupant comfort or productivity and several building factors related to controls, e.g., personal lighting and climate control, outdoor air ventilation rates, light quality, operable windows, etc. (see summaries of several studies at Fisk 2000, Wyon 2000, Jones and Gordon 2004, Olesen

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[66] A larger survey by Gordon and Haasl (1996) also found that "resolving occupant complaints" ranked as the first priority of operations and maintenance staff.

[67] In many instances, simply granting occupants the possibility of controlling their environment improves their comfort; this includes the *perception* that they are controlling their environment, e.g., the non-functional thermostat examples described by Checket-Hanks (2003).

[68] See, for example, Fisk (2000) for more information.

[69] See: www.lightright.org .

2005). Many studies, however, have many confounding factors and a high degree of uncertainty that make productivity-based investments in building systems risky from a management perspective. For example, Fisk et al. (2002) and Federspiel et al. (2002) studied the relationship between outdoor air (OA) ventilation rates per person and employee productivity in a call center. They found that OA ventilation rate per person had an undetectable impact on worker productivity[70] for most conditions. Productivity may increase by around 3% for very high ventilation rates, but confounding factors from the study make this potential gain "far from conclusive". Consequently, although building tenants appear to place a high value on measures related to occupant comfort (BOMA 1999), it remains for the owner/operator to link tenant comfort to financial parameters such as productivity. Without this link, it is difficult to make a convincing business case for substantial investment (Reed et al. 2000). Senior facility professionals tend to believe that buildings affect worker productivity but find it difficult to translate into financial terms. As one senior advisor to the buildings industry puts it, "Everyone knows that facilities have an impact on productivity … but as a practical matter measuring it is so hard you can't prove it" (Sullivan 2003a).

The sheer magnitude of the potential value from increased employee productivity provides the motivation for further research to understand and document the productivity linkage to lighting, environment control, IAQ, etc. Some studies suggest that simply granting occupants the ability (or even the perceived ability) to control their environment can realize meaningful improvement in occupant comfort and productivity (e.g., Wyon 2000). Building design trends over the past 50 years, however, have tended to *decrease* personal control over the environment by replacing individual control over windows and radiators with a "hermetic" building (Hartman 2001).

Building controls vendors are not the only parties that claim that their equipment can enhance occupant productivity and/or sales. Office furniture, lighting[71], and space designers and many other parties attempt to sell their products using productivity enhancement as a value proposition (White 2003). Consequently, building controls vendors compete with numerous other building components for investment and somehow will need to differentiate their claims for productivity gains. In other cases, a corporation may want to project a certain image and will pay more to achieve that goal. To the extent that building controls can contribute to that goal, enhances the value proposition for the controls.

7.2 Reduced Operations and Maintenance Expenditures

Building controls can be sold – and EMCS were initially installed – as a way to reduce building maintenance and operations expenses if the controls vendor can convince the

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[70] In this instance, the average handling time per call served as a proxy for productivity.

[71] For example, Simeonova (2003) describes how organizations ranging from the U.S. Navy to the State Health Department of New York are investigating lighting modifications to improve indoor environments (e.g., to avoid Seasonal Affective Disorder or enhance the healing environment). The Heschong-Mahone Group has carried out multiple studies that suggest a positive correlation between daylighting and student performance, as well as between daylighting and retail sales; see reports at: http://www.h-m-g.com/Daylighting .

owner of the cost-effectiveness of this measure. Indeed, a survey of building operators in larger office buildings found that performing “unscheduled maintenance” and “preventive maintenance” ranked as the second and third priorities of building O&M staff after “resolving occupant complaints” (Gordon and Haasl 1996). The value proposition appears stronger in the centralized controls case, i.e., EMCS. For instance, centralized direct digital control (DDC) control allows the EMCS operator to make temperature set point changes in all zones via the EMCS, whereas pneumatic or local building controls would require manual modification at each terminal unit. In one case, a hospital with a new EMCS (upgraded from a circa 1993 DDC system) collects data from over 100 nodes has enabled and allows building operations personnel to remotely monitor and access the data. The net impact: the operators now perform preventive maintenance based on information from the EMCS, they experienced a “substantial” decrease in trouble calls maintenance, and labor costs decreased by approximately 50%, (ACHRN 2002). Relative to legacy pneumatic controls, DDC requires “significantly less” maintenance, e.g., to maintain calibration (Energy Design Resources 2001).

Looking to the future, opportunities to apply controls in the overall buildings market to reduce operating, maintenance, and energy expenses are somewhat less potent drivers for implement building controls than enhancing the indoor environment. They do appear, however, to have played a substantial role in convincing people who *have* already installed integrated building systems. A survey by BOMA (2000) found that lower operating costs and lower maintenance and repair costs were the two leading drivers for building system integration. Reduced maintenance and operations costs will tend to decreases payback periods for an EMCS relative to considering only energy savings. As Barsoum (1995) notes, however, “the benefits derived from up-front investments are usually too vague to measure, thus monies spent are usually only justified versus energy dollars ‘avoided’”. Hence, although an EMCS does reduce O&M costs, they often do not factor in the economic assessment.

7.3 Indoor Air Quality

Indoor Air Quality (IAQ) affects the design, construction, and operation of ventilation systems. The emphasis on energy savings in the 1970s resulted in building and HVAC design changes that do not always have beneficial effects on the building occupants. In particular, the reduction of infiltration and mechanical ventilation rates significantly decreased the quantity of outdoor air (OA) introduced into buildings to dilute contaminants. Recognition and concern about Sick Building Syndrome (SBS), a term that refers to buildings with high levels of occupant complaints about comfort as well as perceived and actual health effects caused by poor IAQ, began in the mid-1980s. Pollutant sources from several sources can cause and contribute to IAQ problems, including: building occupants, construction materials, building operations/equipment (e.g., copiers), outdoor contaminants introduced via the ventilation system, and contaminants associated with the ventilation system (e.g., microbial growth in ducts). Recently, mold has become a significant concern in the buildings industry (McDonald 2003; ACHRN 2003). Building controls can help to prevent mold, for example, by maintaining positive building pressures to prevent the accumulation of moisture in the building shell.

Lawsuits linked to poor IAQ have heightened the concerns of building engineers, equipment and systems installers, and buildings owners about IAQ. Even without lawsuits, IAQ issues can result in significant expenses to all parties. Poor IAQ can increase absenteeism and degrade the productivity of building occupants. Contaminated HVAC systems require thorough cleaning before resuming operation. Consequently, building controls can enhance their value by helping to prevent IAQ problems from arising and detecting and diagnosing potential problems before they become significant. A Washington, DC-area property manager indicated that his clients have begun to inquire about how they can detect specific IAQ agents. At present, however, he feels that no cost-effective "box" exists for IAQ monitoring that can be readily integrated into an HVAC system; periodic monitoring represents the main option (Stites 2003).

7.4 Reduced Energy Expenditures

Reducing energy expenditures is another, more moderate value proposition for building controls. Although utility expenses currently account for a very small portion (~1%) of total building expenses (per Table 6-1), they do account for a significant fraction (~30%) of operating expenses (Figure 6-1). The potency of this value proposition depends on gas and electric costs. For example, EMCS first became valued for their ability to reduce energy costs during the energy crises of the 1970s. Similarly, the potential value of building controls increases in regions with higher energy costs, most notably regions with high peak electric demand charges[72] (e.g., the Northeast). On average, peak demand charges account for about 40% of commercial building electricity expenditures (see Appendix C). This provides a financial incentive for buildings on electric rate structures that includes peak demand charges to avoid establishing a new high demand level, particularly for ratcheted[73] utility rate structures.

Lighting and HVAC account for about 75% of commercial sector peak electricity demand (see Figures 7-1 and 7-2[74]). Building controls have the potential to achieve substantial reductions of both end uses.

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[72] Peak demand charges are usually assessed on a $/kW basis for the highest average kW power draw, e.g., over a 15-minute or one hour period.

[73] In a ratchet structure, the maximum peak electric demand over a period of several months is assessed for all months over that period.

[74] The different end uses displayed for each figure reflects the data available from each source.

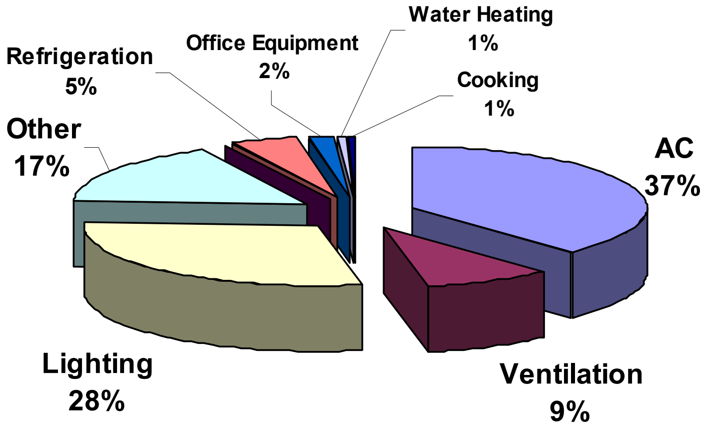

Figure 7-1: Breakdown of Commercial Sector Electric Peak Demand in 1999 by End Use (based on Brown and Koomey 2002)

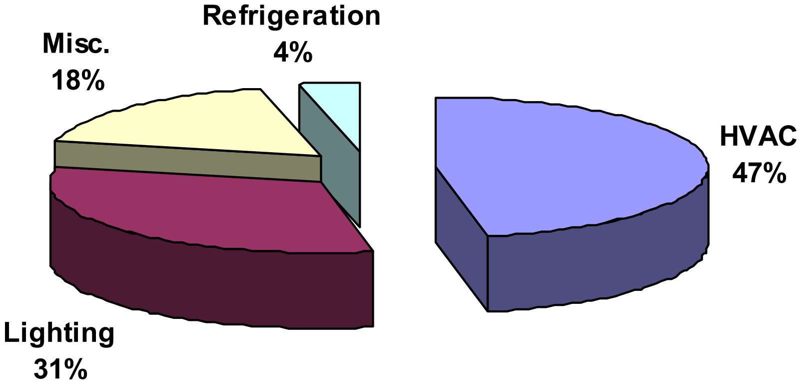

Figure 7-2: Breakdown of Commercial Sector Electric Peak Demand in New Jersey by End Use (based on Nadel et al. 2000)

This indicates that building controls can add appreciable value by incorporating peak-shaving functions, such as switching off portions of indoor lighting or allowing indoor temperature setpoints to rise during periods of notably high peak demand. Historically, some EMCS have had the capability to implement measures that limit peak demand, e.g., an EMCS-based building system optimization for a San Francisco hotel with a real-time pricing tariff achieved upwards of 20% annual energy cost savings based on peak demand reduction (Kammerud et al. 1996). Typically, however, a relatively small percentage of building operators with this capability actually use it (see Section 4.4).

Products such as demand response systems, have begun to come to market that communicate requests from utilities for peak electric demand, e.g., via e-mail or phone. In many cases, they enable customers with multiple facilities in a utility district to coordinate their demand management activities and, in some cases, shed peak loads automatically at locations using pre-determined peak demand reduction strategies (Motegi et al. 2003). More advanced products can automatically manage building system operations to optimize total building energy expenses by managing peak demand, including in response to real-time pricing[75], while maintaining occupant comfort. Similarly, these products enable optimization of energy expenses for a portfolio of buildings by rotating peak shedding between buildings to maximize peak demand reduction while taking care to avoid uncomfortable conditions at all locations. Section 9.7 discusses these systems further.

7.5 Security

The market for commercial building security systems is of the same order as that for building controls. In addition, many EMCS manufacturers view security systems as a strong candidate for integration with traditional building controls. Consequently, security concerns may influence the future market for building controls, particularly centralized systems. Three aspects of security, terrorist threats, conventional building security, and information security, warrant further discussion.

Awareness of the potential impact of terrorist threats on building occupants became much more tangible and heightened after the terrorist attacks of September 11, 2001. In particular, attention has centered on the risk of biological and chemical agents released in a building by individuals or via the ventilation system. The reaction of most building owners to these threats has been negligible, primarily for two reasons. First, most owners perceive that their building(s) has a very low risk of suffering an attack. Second, the sheer number of vulnerabilities makes the cost of undertaking effective countermeasures prohibitive (Buildings 2002; Johnson 2003). The Defense Advanced Research Projects Agency (DARPA) is performing work in this area[76], but daunting challenges remain to developing systems for actual buildings. Consider, for instance, the modifications to HVAC systems required to mitigate a chemical or biological attack introduced via the outdoor air intake. A first line of defense might be to install devices that could remove or neutralize some portion of the chemical and/or biological agents, e.g., HEPA filters and/or UV light. These both result in substantial up-front and recurring (operating) costs that are not limited to the cost of the equipment itself. For instance, the increased pressure drop of the filters would require retrofitting bigger ventilation fans and motors, with a substantial cost impact, while also increasing ventilation fan energy consumption. Furthermore, building systems would require installation of additional sensors to detect the introduction of a wide range of potential agents into the building before they had inevitably spread throughout the building. At present, reliable sensors do not exist for detecting many potential contaminants (ASHRAE 2003a). In any case, if successful, this approach would only neutralize agents

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[75] The future of real-time electric pricing is unclear. Although some utilities offer electric rates that vary throughout the day according to the cost of electricity supplied to the utility, the trend towards nationwide adoption has slowed with many utilities suspending their existing real-time rate structures.

[76] More information is available at: http://www.darpa.mil/spo/programs/immunebuilding.htm .

introduced from the outdoor air intakes, leaving it vulnerable to a person dispersing agents inside the building, drilling into ductwork, etc. (Johnson 2003).

Future codes could conceivably include terrorism-related requirements that affect building systems (see, for example, Hadley 2002 for potential measures). General sentiment, however, runs counter to mandating any specific security-related measure or recommending measures without a thorough examination of economic, energy, maintenance, and IAQ impacts (ASHRAE 2003a). Development of small-scale, inexpensive and reliable contaminant sensors could enable widespread deployment of selective biological and chemical contaminant sensors within several years (Schell 2003; CABA 2003b). On the other hand, effective HVAC system *response* based on inputs would require further evolution.

Instead of focusing on potential terrorist threats, building "industry leaders believe the U.S. facilities market must continue to focus its security initiatives on beefing up everyday safety and emergency response rather than shift toward concentrated anti-terrorism measure" (Buildings 2002). Indeed, a survey by BOMA and the Urban Land Institute of facilities professionals reflects these priorities. Fire safety easily rated as the primary security issue (~60%), followed by civil unrest and power disruptions (~35% each); terrorism (~12%) and biohazards (~7%) were much lower concerns. Liability concerns also motivate focusing on basic security. One building security executive notes that insurance companies may not cover business interruption assistance costs if the building owner has neglected to perform an appropriate security assessment or to implement appropriate steps (CABA 2003b).

On the other hand, the profile of information/data security continues to rise. According to Buildings (2002), building alarm monitoring, lobby security controls, surveillance cameras, and employee background checks ranked as the most important security measures before September 11th. After September l1th, vendor security – not biological or chemical attacks – became more important. Presumably, this reflects concerns about the security of proprietary data shared with vendors. As building systems share more information and remote building control and access to building information via the Internet becomes more common, the potential impact of information (and network) security breaches correspondingly increases. For example, people could "attack" the building controls system[77] and gain control over some or all of the building functions. The intent of the hackers could range from benign (e.g., playing with lighting systems) to more serious (e.g., compromising the physical security system). A manager of several buildings notes that active but forgotten phone lines and "backdoor" system access passwords can pose significant security risks in larger organizations (Levi 2003). Web-accessible building controls have leveraged approaches used for data security by information technology professionals, such as encryption and firewalls to establish isolated virtual private networks (VPNs), to secure building control systems (DeNamur 2003).

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[77] Holmberg (2003) provides a succinct overview of some ways that people can access and attack building control systems via IT systems, while also presenting countermeasures to mitigate security vulnerabilities.

Overall, building controls that include or enhance security functions can enhance their perceived value. An initial discussion of potential synergies and conflicts between building energy efficiency and security describes several ways that building controls can influence building security, including increased monitoring of equipment and spaces, greater spatial granularity in thermal and ventilation control, and occupancy sensors (Harris et al. 2002). For commercial buildings, however, security systems cannot evolve to the point where they become intrusive or inconvenient to occupants and the building staff. Fundamentally, a large portion of commercial buildings is quasi-public, they are places where people work and shop, and access frequently and easily. When security becomes inconvenient, it compromises the basic function of the buildings while also driving people to try to circumvent the security measures.

8 The National Energy Impact of Building Equipment and System Faults

The building commissioning literature, targeted building equipment and systems surveys, and anecdotal information suggest that ill-functioning building systems and equipment waste significant quantity of energy. Most buildings maintain basic levels of functionality, but many suffer from a departure from intended performance due to a wide range of "faults." In this context, faults denote deviations from intended or as-designed building equipment and systems performance that compromise the operational efficiency of equipment and system due to improper installation, insufficient maintenance, or a lack of attention to operations. A significant volume of literature suggests that commissioning of existing buildings typically reduces total building annual energy consumption by 5% to 20%, with higher values (up to 30%) in some buildings (see Section 9.1). In addition to increasing building energy consumption, faults may degrade climate control and occupant comfort.

The actual energy wasted by different buildings varies greatly and depends on the types of systems in a building, how well building operators maintain the building, and what failures occur. In general, the energy use impact of faults depends on the system details. Some building faults do not have a significant effect on building energy consumption. This often occurs when a fault results in decreased occupant comfort. If a fault results in uncomfortable indoor conditions, it typically generates complaint calls[78] and the problem is addressed. For example, a packaged AC unit with very low refrigerant charge levels will not have sufficient capacity to meet cooling loads on hot days. On a hot day, the occupants notice and complain about the uncomfortable conditions, which will usually lead to a service call and subsequent identification and resolution of the problem. In other cases, building operators or occupants may respond to faults by making adjustments to building systems that resolve the problem without increasing energy consumption. For instance, a space temperature sensor that drifts out of calibration generally leads to adjustment of thermostat setpoints and little change in space temperature levels. On the other hand, a failure that does not impact occupant comfort may escape detection and persist for a long time. If a supply air or chilled water temperature sensor drifts out of calibration, it causes the air or chilled water temperature to increase or decrease. The building operator or tenants often will not notice the problem because it may not affect their comfort. Because the fault is not noticed and fixed, energy use often increases. Other faults may actually reduce energy consumption, for example, an incorrect damper position that reduces the intake of outdoor air for a building located in a hot and humid climate.

Although past commissioning studies provide a basis for a top-level estimate of the total energy impact of building faults, estimates of the national energy impact of specific

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[78] A survey of larger office building operators found that responding to occupant complaints uncovered 41% of building problems, routine inspection discovered 30%, and examination of EMCS data found about 19% of problems (Gordon and Haasl 1996).

building faults have yet to be developed. A breakdown of the national energy impact of specific building faults can help to identify and prioritize:

- The development of fault-tolerant equipment and controls;
- The development of cost-effective diagnostics that address more common faults with high energy impact;
- Modifications to building systems and equipment implementation practices to decrease installation-related faults and the likelihood of future faults, and
- Building maintenance activities that address common faults with high energy impact.

This report section presents evaluations of the faults that have the greatest impact on commercial building energy consumption.

8.1 Fault Selection Process

Figure 8-1 summarizes the fault selection process.

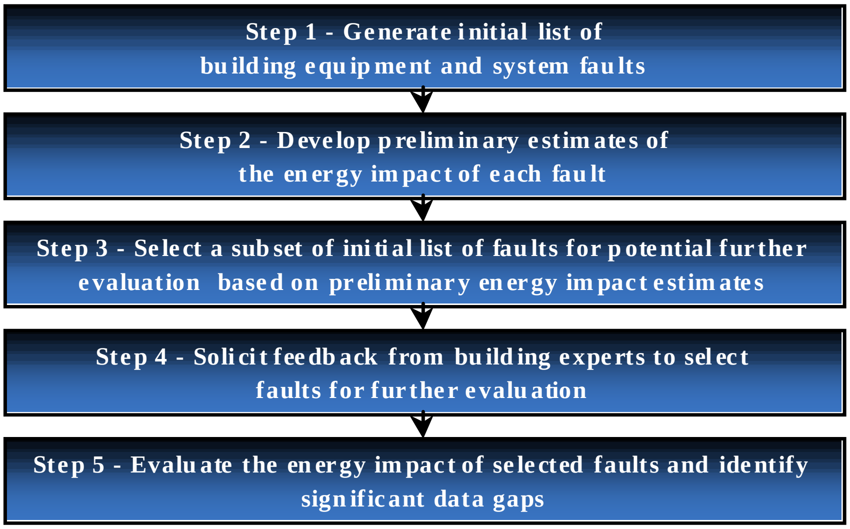

Figure 8-1: Fault Selection Process

TIAX performed a literature review to identify problems that arise in building HVAC, lighting, water heating, and refrigeration systems and may increase building energy consumption (*Step 1*). This uncovered more than 100 faults that occur in commercial building HVAC, lighting, and water heating systems (see Appendix B for the entire list). Information found in the literature was used to calculate each fault's estimated annual energy consumption impact, AEC_{Fault}, which equals the product of three different parameters:

$$AEC_{Fault} = AEC_{RE} \cdot Frequ_{Fault} \cdot Degradation_{Fault} \ .$$

AEC_{RE} – The *Relevant Annual Energy Consumption* equals the quantity of national energy consumption potentially impacted by the fault. These values come from breakdowns of energy consumption by equipment and system type.

$Frequ_{Fault}$ – The *fault frequency* in relevant equipment and system type, i.e., how often the fault occurs such that it causes an appreciable increase in energy consumption beyond as-intended performance.

$Degradation_{Fault}$ – The *average percent increase in energy consumption* due to the fault.

The preliminary AEC_{Fault} estimates for each fault (*Step 2*) were used to identify a subset of the initial list of faults for possible further evaluation (*Step 3*). TIAX distributed the shorter list of faults to buildings experts for their feedback. In particular, the team wanted to determine if the fault list omitted any key faults or included any faults that have little energy impact. Consequently, feedback focused on experts with extensive real-world experience in buildings, including people associated with energy service companies (ESCOs), building diagnostics firms, and building commissioning. Taking into account the feedback received, TIAX arrived at the final list of faults selected for evaluation (see Table 8-1).

Table 8-1: Faults Selected for More Refined Evaluation

Fault Type	Fault
Lighting and HVAC	Lights or HVAC Left on When Space Unoccupied
Air Distribution	Duct Leakage
Air Distribution	Dampers not Working Properly (Actuator failure, blades stuck, etc.)
Air Distribution	Airflow Not Balanced
Air Distribution	Insufficient Evaporator Airflow
Controls	Software Programming Errors
Controls	Improper Controls Hardware Installation
Controls	Improper Controls Setup / Commissioning
Controls	Control Component Failure or Degradation
Waterside Issues	Valve Leakage
Refrigeration Circuits	Air-Cooled Condenser Fouling
Refrigeration Circuits	Improper Refrigerant Charge

The evaluation of the energy impact of the selected faults focuses on developing a more refined national energy impact estimate. Specifically, TIAX performed a detailed review of information relevant to each fault found from a thorough literature review and search. Often, this process revealed data gaps in crucial areas. The writeup for each fault clearly identifies the missing data and attributes, as well as data uncertainty, and suggests actions to obtain the needed data.

An explanation of the derivation of the energy impact calculation parameters for a single fault, in this case "Improper Refrigerant Charge," provides insight into how the methodology was applied to all of the key faults. The *fault relevant AEC*, AEC_{re}, is the quantity of national energy consumption potentially affected by the fault. In theory, this would equal the AEC of all commercial building equipment that uses compressors, or 1.8 quads. In practice, supermarket refrigeration systems and chillers are much less likely to have improper refrigerant charge levels that degrade system performance because those systems tend to be better maintained and often have built-in diagnostic systems to alert users of problems and/or refrigerant receivers. Thus, the relevant AEC equals about 1.1 quads, of which packaged unitary AC accounts for 80%. The *fault frequency*, $Frequ_{Fault}$, range of 40% to 80% reflects the authors' synthesis of field measurements of packaged unitary AC charge levels from several sources (Downey and Proctor, 2002; Modera and Proctor, 2002; Jacobs *et al.*, 2003; Goody *et al.*, 2003; Davis *et al.*, 2002; Hewett *et al.*, 1992; Carl and Smilie, 1992; Hoover, 2001). The *average percent increase in energy consumption* due to the fault, $Degrade_{fault}$, comes from analytical estimates for EER degradation (Davis *et al.*, 2002; Jacobs *et al.*, 2003; Modera and Proctor, 2002) and laboratory testing to evaluate how different refrigerant levels effect the EER and SEER ratings of small (around 3-ton) packaged unitary AC (Farzad and O'Neal, 1993; Breuker and Braun, 1998; Goswami *et al.*, 2001). The data sources estimated different values for the energy impact of different refrigerant charge levels, and the energy impact range of 5% to 15% reflects the authors' evaluation of the universality of the different sources. Ultimately, the total fault energy impact range, AEC_{fault}, equals the product of the estimated ranges of the three factors, i.e.:

Lower Value = 1.1 quad (relevant energy)*40% (prevalence) *5% (energy impact) = **0.02 quad**, and

Upper Value = 1.1 quad (relevant energy)*80% (prevalence) *15% (energy impact) = **0.12 quad**.

8.2 Summary of Energy Consumption Impact

The excess energy consumption caused by building faults occurs in the context of the approximately 17 quads of primary energy consumed by commercial buildings (see Table 8-2).

Table 8-2: Commercial Building Annual Primary Energy Consumption Breakdown (circa 2000)

End-use	Primary Energy [quads]	% of Total	Source
Lighting	4.2	27%	Navigant Consulting (2002)
Water Heating	1.2	8%	EIA (2003)
Refrigeration	1.0	6%	ADL (1996)
Supermarket Systems	*0.33*	*2%*	
Walk-In Refrigerators , Freezers	*0.18*	*1%*	
Ventilation/Pumping	1.5	10%	ADL (1999)
Supply/Return Fans	*0.7*	*5%*	
Exhaust Fans	*0.5*	*3%*	
Water Pumps	*0.1*	*1%*	
Other Parasitics	*0.1*	*1%*	
Heating	1.7	11%	ADL (2001a)
Furnaces	*0.3*	*2%*	
Boilers	*0.4*	*2%*	
Packaged Unitary	*0.4*	*3%*	
Other Heating Equipment	*0.5*	*4%*	
Cooling	1.4	9%	
Packaged Unitary AC	*0.7*	*5%*	
Chillers	*0.4*	*3%*	
Other Cooling Equipment	*0.2*	*1%*	
Office & Telecommunications	1.1	6%	ADL (2002)
Cooking Equipment	0.5	3%	ADL (1993)
Other Building End-Uses	1.7	10%	BTS (2003)
Adjustment[79]	2.9	17%	BTS (2003)
Total	17.2		EIA (2003)
U.S. Energy Consumption	97		EIA (2003)

Note: sums may not equal totals due to rounding.

The 13 faults studied account for about one quad of commercial building energy consumption (see Table 8-3), or 11% of energy consumed by HVAC, lighting, and larger refrigeration systems[80] in commercial buildings. Three faults, “HVAC Left on When Space Unoccupied,” “Lights Left on When Space Unoccupied,” and “Duct Leakage,” appear to account for at least half of the total fault energy impact.

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[79] This represents an adjustment to commercial sector energy consumption by EIA to reconcile differences between sources (BTS 2003). In theory, all of the end-use estimates could be increased by the ratio of commercial sector energy consumption with the adjustment to that without, i.e., 17.2/14.3 = 1.20.

[80] Larger refrigeration systems include supermarket refrigeration systems and walk-in system.

Table 8-3: The AEC Impact of Faults Selected for Evaluation

Fault	AEC [quads]
Duct Leakage	0.30
HVAC Left on When Space Unoccupied	0.20
Lights Left on When Space Unoccupied	0.18
Airflow Not Balanced	0.070
Improper Refrigerant Charge	0.070
Dampers not Working Properly	0.055
Insufficient Evaporator Airflow	0.035
Improper Controls Setup / Commissioning	0.023
Control Component Failure or Degradation	0.023
Software Programming Errors	0.012
Improper Controls Hardware Installation	0.010
Air-Cooled Condenser Fouling	0.008
Valve Leakage	0.007
TOTAL	1.0

The estimated likely range of the energy impact is quite broad, i.e., between 0.34 and 1.8 quads. Placed in the context of commercial buildings, the faults account for between 2% and 11% of all energy consumed by commercial buildings. Considering only systems primarily affected by the faults, that is, HVAC, lighting, and large refrigeration system energy consumption, fault-related energy waste equals between 4% and 20% of the energy consumed by those end uses. This range is broadly consistent with the 5% to 20% energy savings potential range found for retrocommissioning projects (see prior discussion).

The following subsections present the analyses for the individual faults. Each subsection includes:

- Summary Table – Top-level summary of key information for each fault.
- Fault Overview – What the fault is and common reasons why it arises.
- Fault Energy Impact – Overall energy impact of the fault and tabular summary of all data relating to the fault energy impact (prevalence, energy impact, fault context) found during the literature review; may include separate tabulation for information from detailed commissioning reports (SBW Consulting 2003).
- Quality of Data – An evaluation of the key data gaps found in evaluating the literature that increase the uncertainty of the energy impact ranges and how the gaps impact the ranges; potential ways to address the gaps and reduce the uncertainty of the energy impact ranges.
- References – Complete references for all data and information used in that subsection.

8.3 HVAC and Lighting Operation During Unoccupied Hours

Table 8-4: Summary of HVAC and Lighting Operation During Unoccupied Hours

Characteristic	Result	Comments
Systems Impacted by Technology	All HVAC and Lighting	
Niches of High Fault Energy Impact	Packaged RTU supply air fans that take in large quantities of outdoor air operating in hot and humid climate.	
Relevant Primary Energy Consumption (quads)	8.7	All HVAC and lighting energy
Prevalence of Fault	See Comments	Scheduling issues account for a significant portion of building faults on a frequency and energy impact basis Unintentional lighting ~5-10%; intentional lighting during unoccupied hours may account for an additional 12%. • HVAC prevalence of 15-30%
Energy Impact of Fault	10 – 50%; see end use breakdowns	• Unintentional lighting ~10-30% • Intentional lighting (e.g., nighttime security lighting) – average ~50% (depends on portion of lights on) • HVAC ~10-30%
National Energy Impact of Fault [quads]	0.1 – 0.8	• Unintentional lighting 0.02 – 0.13 • Intentional lighting up to an additional 0.25 quad • HVAC ~0.07-0.4 quad
Major Data Gaps	More concise estimate of percentage of HVAC systems that unintentionally operate after-hours	
Can Diagnostics Address this Issue?	Yes, using time series measurements of building and major plant equipment (e.g., chiller) energy consumption (also see Section 9.10)	

8.3.1 Fault Overview

Most buildings do not operate “around the clock.” Building survey data indicate that about 80% of buildings that do not operate around-the-clock[81] set back their thermostats (or turning off cooling systems entirely) to reduce energy consumption during unoccupied periods (EIA 1999). Similarly, about 98% of buildings that could reduce lighting at night claim to reduce at least a portion of their lighting (EIA 1999). Often, building operators leave on a portion of lights in many buildings for security or commercial reasons.

In practice, however, some building operators unintentionally leave their lighting on and do not set back their HVAC systems while unoccupied, wasting energy by providing unneeded/unused lighting and space conditioning. This can occur due to malfunctioning, unprogrammed, or incorrectly programmed setback thermostats. Similarly, EMCS can have inappropriate schedules or lack schedules, e.g., due to improper configuration, system reset after a power failure, or user overrides of initial parameters. Often, unneeded after-hours lighting and HVAC operation can go undetected, precisely because the building is not in operation when the fault occurs.

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[81] Buildings that do not operate “around the clock” account for 80% of lit floorspace (EIA 1999).

8.3.2 Fault Energy Impact

Lighting operation during unoccupied hours increases lighting energy consumption by an amount linearly proportional to the additional operating hours[82]. The energy impact of prolonged HVAC operation is more complex and depends upon the time of year, climate, and building type. For example, operation of ventilation systems at night can reduce cooling load under certain conditions by precooling the building prior to the occupied period.

In addition, many spaces have intermittent daytime occupancy patterns, such as bathrooms and conference rooms. Occupancy-based strategies such as occupancy sensors integrated with lighting controls exist for reducing both lighting and HVAC energy consumption during occupied periods. The fault analysis presented in this section, however, focuses on operation during unoccupied periods and does not take into account the additional energy “wasted” during daytime periods. Strategies that reduce lighting and HVAC system operation during occupied periods can save additional energy but are not considered to be fixing a “fault”.

Appendix E presents the Energy Impact Data found for this fault and the References for the data. The available data indicate that it is not uncommon for buildings with EMCS, i.e., presumably with operators that intend to reduce lighting and adjust HVAC setpoints during unoccupied periods, to have unneeded lighting and/or HVAC operation during unoccupied periods. For example, about 15% of buildings without 24-hour operation[83] do not adjust their HVAC setpoints during unoccupied periods (CBECS 1999). Another study, of more than 200 small RTUs, found that about 30% have supply fan schedules that coincide with unoccupied periods (Architectural Energy 2003). The wide range of sources consulted show that the energy impact of HVAC operation during unoccupied periods can range from negligible (e.g., lighting for a relatively small area or a small exhaust fan) to as much as ~30% (e.g., when buildings located in hot, humid climates do not turn off supply air blowers or set back HVAC systems during unoccupied periods).

For lighting, almost all (>98%) buildings that do not operate around the clock do implement lighting shutdown over at least a portion of the unoccupied space. Nonetheless, CBECS data suggest that lighting that remains on during unoccupied periods equals about 12% of total lighting energy consumption. Lights remain on, however, for security (and other) reasons and the portion of this lighting that represents waste is not known. Industry estimates suggest that unnecessary lighting may equal as much as 50% of this lighting (Petrow 2004).

In total, it appears that between 15 and 30% of buildings have HVAC that operate during unoccupied periods, which increases HVAC energy consumption by 10–30%. Significant

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[82] This assumes that the same lights operate during occupied and unoccupied hours

[83] Buildings without 24-hour operation account for ~81% of floorspace (EIA 1999).

fault-related unoccupied lighting occurs in perhaps 5-10% of additional floorspace and increases lighting energy consumption in buildings where this occurs by 10-50%. Additional *intentional* lighting during unoccupied periods accounts for up to 6% of total lighting energy consumption. It is not clear, however, how much of this energy consumption can be “fixed” because the lighting presumably serves a purpose, such as security.

8.3.3 Quality of Existing Data

Although CBECS provides very useful data for the prevalence of buildings that intentionally do not set back their HVAC systems or turn off their lights when unoccupied, the prevalence of *unintentional* unoccupied operation remains highly uncertain. In addition, it is not clear what portion of unoccupied lighting energy (calculated from CBECS) serves a useful purpose, such as security, or represents energy waste.

Table 8-5: Data Gaps and Possible Solutions - HVAC and Lighting Operation During Unoccupied Hours

Data Issue	Potential Solution(s)
High uncertainty for fault prevalence	Building evaluations (i.e., inspections, not surveys, to understand *unintentional* lighting) to determine approximate floorspace percentages with lights on and HVAC not set back
Portion of unnecessary lighting operation when building unoccupied	Building evaluations

8.4 Duct Leakage

Table 8-6: Summary of Duct Leakage Fault

Characteristic	Result	Comments
Systems Impacted by Technology	All ducted systems, i.e., fan, cooling and heating systems in central (except FCU) and packaged HVAC systems	
Niches of High Fault Impact	Light commercial buildings	• Rarely commissioned, detection of leakage highly unlikely • Construction practice often does not use an A&E, which can compromise construction practices and oversight
Relevant Primary Energy Consumption (quads)	3.1	All heating, cooling, and parasitic energy associated with ducted central and packaged HVAC systems.
Prevalence of Fault	Small buildings >80%; roughly 50% for larger buildings	Most commercial duct systems appear to leak at least 5% of total airflow; very limited data for larger commercial buildings
Energy Impact of Fault	Varies much from building to building and with ventilation system type	25-35% air leakage ratio (ALR) typical for smaller buildings, 5-15% for larger buildings; Impact on heating, cooling and ventilation varies with system type (CAV versus CAV)
National Energy Impact of Fault [quads]	0.15 – 0.4	See "Fault Energy Impact" section for details
Data Gaps	• Very high uncertainties in many reported duct leakage flow measurements • Almost all data from California and Florida buildings (only known simulations for California) • Unclear energy impact of duct leakage for different system types • Percentage of ducts located outside conditioned space unclear for smaller buildings • Unclear distribution of faults by root cause; causes include: poor installation practice, gradual seal degradation, or sudden failure	
Relevant Control and Diagnostics Applications & Issues	• Diagnostic approaches in development (see Section 9.4) • Commissioning of ducts via testing • Airflow sensors/measurements often have high uncertainties	

8.4.1 Fault Overview

All ducts have some degree of leakage, leading a researcher to estimate a lower-bound of 3% to 5% (Wray 2004) which exceeds the ASHRAE recommended leakage levels by roughly three- to five-fold. Measurements of *typical* duct leakage levels in commercial buildings, however, indicate that duct leakage exceeds the ASHRAE recommended leakage classes by roughly a factor of 20 (ASHRAE 1998; Fisk et al. 1998). Delp et al. (1997) observed several light-commercial duct systems riddled with faults, including torn and missing external duct wrap, poor workmanship around duct take-offs and fittings, disconnected ducts, and improperly installed duct mastic. Duct connections (e.g., diffusers) are particularly leaky. Even with properly sealed ductwork, thermal cycling damages the adhesives in sealants – especially the rubber-based adhesive in duct tape – thus increasing leakage over time (Sherman and Walker 1998). Pressure cycling also can wear out duct seals over time by pulling the joints apart – especially when the ductwork is not adequately supported during installation (Hamilton 2002).

Heated or chilled air that leaks from the ducts into unconditioned space increases the duty cycle of the heating or cooling equipment. As a result, a VAV blower also must run “harder” to deliver the required heating or cooling to the conditioned space.

8.4.2 Fault Energy Impact

The energy impact of duct leakage differs between CAV and VAV systems. In constant air volume (CAV) systems, the supply and return fans run continuously and duct leakage does not change ventilation energy consumption. Duct leakage can, however, increase heating and cooling loads. Duct leakage in ducts located outside the building’s thermal barrier transfer heated or cooled air to the outdoor space, increasing heating and cooling energy consumption by approximately the air leakage ratio of these ducts. On the other hand, ducts located within the thermal barriers have a more ambiguous impact on heating and cooling energy consumption. Some portion of the heated or cooled air leaked from the ducts may reach the intended space. Many CAV systems run ducts through a ceiling plenum that also serves as the path for the return air. In that case, the heated or cooled air leaked from the supply ducts conditions the return air. The ultimate energy impact of the duct leakage thus depends on the proportion of the return air that becomes supply air (relative to that exhausted from the building).

Duct leakage has a more complex impact on VAV system energy consumption due to the variable response of the system and greater complexity and (often) scale of the systems (Wray and Matson 2003). Duct leakage typically increases VAV blower energy consumption because the duct leakage impedes the HVAC system from achieving temperature setpoints in zones further from the central air-handling unit. This causes the VAV boxes open up further to increase the supply fan flow and energy consumption. In turn, the additional blower energy causes cooling loads to increase while reducing reheat energy consumption[84]. If the supply air leaks into conditioned spaces, it can lead to over-heating or –cooling of those spaces while simultaneously failing to satisfy the needs of other spaces in the same building or zone. A VAV system where the supply air passes through a ceiling plenum used for return air leaks supply air into the plenum and “conditions” the return air in the same manner as discussed in the prior paragraph.

Many of the duct leakage data have very large uncertainties in duct air leakage ratios (ALRs), i.e., +/10% of total system flow – or greater. When available, the Energy Impact Data in Appendix E notes uncertainty levels for different sources. Measurements made with passive flow hoods have notably larger potential uncertainties (potentially +/-20% or greater due to calibration, nonuniform flow, and the resistance of the hood; Walker et al. 2002). Methods based on active flow hoods have much smaller errors and recent measurement techniques, such as the “Delta Q” and “Delta Q Plus” methods, reduce the error to under +/-4% of system air flow (Andrews 2002; Walker et al. 2002).
The available data (see Appendix D) suggest that most smaller – and at least half of larger – commercial buildings have appreciable levels of duct leakage. Furthermore, even well-

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[84] In essence, fan energy dissipated downstream of the cooling coil supplants traditional reheat.

sealed duct systems have an ALR of about 5%, which is more than twice ASHRAE guideline for rectangular ducts (Wray 2004). Smaller commercial buildings appear to have duct leakage of between 20% and 35% of system airflow (Cummings et al. 1996, Delp et al. 1997, Delp et al. 1998b, Jacobs and Williams 2002, Modera and Proctor 2002). More limited data indicate that larger commercial buildings with central air handling units have lower leakage rates than smaller buildings with unitary-based ducting, likely between 5 and 20% (Fisk et al. 1998, Xu et al. 1999, Luskay and Sellers 2002, Diamond et al. 2003).

The location of the ducts and duct leakage usually affects the energy impact of duct leakage. Approximately half the total ductwork in a small commercial building lies within the thermal barrier (Delp et al. 1997), while most of the ductwork for larger (several story) buildings lies within the thermal barrier (Modera 2000). Simple analyses based on the above data ranges and Wray and Matson (2003; for VAV systems, see Appendix in Section 8.4.4) indicate that duct leakage has the following energy impact for different systems:

- In packaged systems in smaller buildings (primarily CAV), heating and cooling energy each increase by about 13-26%[85];
- In central CAV systems in central systems, heating energy and cooling energy each increase by about 5-15%[86], and
- In central VAV systems, heating energy consumption increases by roughly 8% while cooling energy decreases by roughly 2%[87].

Based on the above findings, duct leakage increases cooling, heating and fan energy consumption by 0.25 to 0.4 quads nationally.

8.4.3 Quality of Existing Data

Few duct leakage data measurements have been performed for central systems in larger buildings and most measurements for smaller HVAC systems have been carried out in California or Florida (somewhat older data). In addition, the annual energy impact of duct leakage for different system types in different climates is not well understood.

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[85] Based on an average duct leakage ratio range of 25 to 35%, with 50% of return air exhausted from the building and the percentage of ducting lying within the conditioned space ranging from 0 to 50%.

[86] Based on an average duct leakage ratio range of 10 to 20% for half of buildings, 5% for other half, with 50% of return air exhausted from the building and all ducting lying within the conditioned space.

[87] Based on California case evaluated in Section Appendix.

Table 8-7: Data Gaps and Possible Solutions for Duct Leakage

Data Issue	Potential Solution(s)
Very little leakage data collected for larger buildings with central air-distribution systems	Measure leakage in larger buildings with central air-distribution systems
Most data available for California and Florida locations only	Evaluate ducts and perform simulations for locations with high HVAC energy consumption, such as the Midwest or Texas
Unclear energy impact of duct leakage in buildings where ducts lie within thermal barrier	Simulations to evaluate the impact of duct leakage on building heating and cooling loads
Very large uncertainty in many duct ALR measurements	Measure duct leakage using more accurate duct leakage procedures (see Andrews 2002; Francisco et al. 2002; Walker et al. 2002)

8.4.4 Appendix – Wray and Matson (2003) Results

Wray and Matson (2003) simulated VAV system performance for six degrees of duct leakage (5 to 20%) in three vintages of buildings (1980s, 1990s, and projected 2005 California Title 24), in three Californian cities (Oakland, Pasadena, and Sacramento). They reported energy consumption values for supply fan, return fan, cooling coil, reheat coil, chiller, cooling tower, and boilers for all 54 cases. Their results provide a feel for the general impact of duct leakage on VAV system energy consumption in moderate and warmer, dry climates. Figure 8-2 reports energy consumption simulation results for different central HVAC system components of a 1990s-vintage office building located in Sacramento as a function of duct leakage level. Note that the study takes 5% as the baseline leakage value for commercial buildings (Wray 2004).

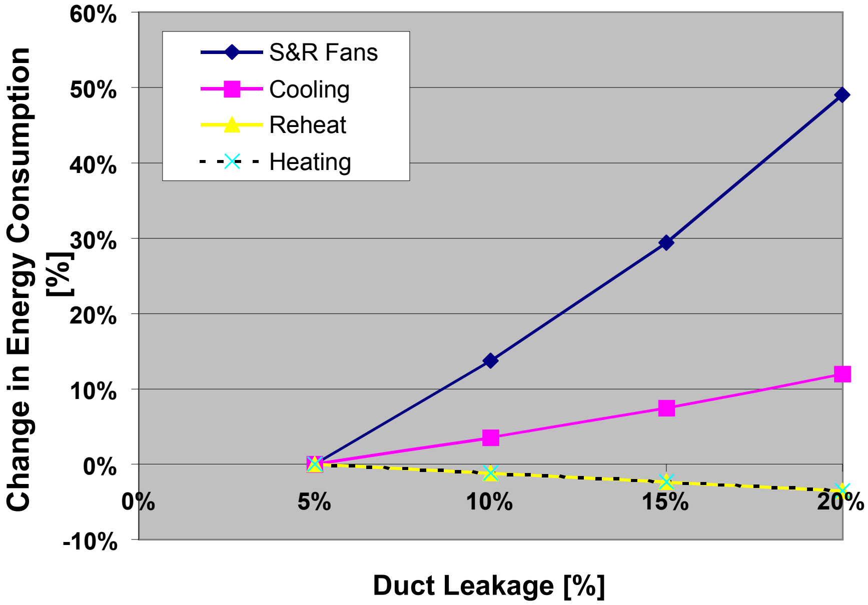

Figure 8-2: Impact of Duct Leakage on Building Energy Consumption for a VAV System in a Sacramento Office Building (from Wray and Matson 2003)

As expected, supply and return (S&R) fan energy increases dramatically with leakage. This reflects that, for an ideal blower, fan power increases with the cube of flow rate. Cooling energy consumption, on the other hand, exhibits a more moderate increase due to the re-circulation of some of the cool air leaked into the return ceiling plenum into the supply air. Heating energy consumption, on the other hand, actually decreases because of the increased fan energy dissipated in the airstream, in essence substituting electric fan energy for reheat energy.

8.5 Dampers Not Working

Table 8-8: Summary of Dampers Not Working

Characteristic	Result	Comments
Systems Impacted by Technology	All systems which use dampers to control flow of air. Specific examples include the following. • Economizers • Mixing dampers (for mixing of outdoor and return air). • VAV boxes (generally called valves) • Dual-duct system terminal unit mixing boxes • Face/bypass dampers • VAV air-bypass dampers, Blower throttling dampers. • Relief Dampers • Smoke Dampers	
Niches of High Fault Impact	Economizer dampers in light commercial buildings	• Rarely commissioned, detection of problems less likely • Higher exposure to damaging effects of weather (rooftop units)
Relevant Primary Energy Consumption (quads)	3.1	All heating, cooling, and parasitic energy associated with ducted central and packaged HVAC systems.
Prevalence of Fault	25 – 40%	Estimate of prevalence of economizer damper problems in packaged rooftop units; based on focused studies.
Energy Impact of Fault	10 – 30%	Estimate for economizers
National Energy Impact of Fault [quads]	0.02 – 0.1	See estimate details below (Table 8-9)
Major Data Gaps	Most damper failure information is for rooftop unit economizers— little data for central system air-handling units and other types of dampers.	
Can Diagnostics Address this Issue?	Yes, see Section 9.2	

8.5.1 Fault Overview

Dampers fulfill a range of functions in HVAC systems, such as those listed in Table 8-9. Several causes can result in the failure of damper systems, including: (1) corrosion and degradation that cause dampers or their actuators to seize, leaving the damper in a fixed position; (2) broken linkages that prevent dampers from operating properly; (3) economizer control system failure, and (4) failure of sensors that a controller uses to determine proper damper position.

8.5.2 Fault Energy Impact

The energy consumption associated with damper failure depends on the type of failure as well as the damper function. In order to have a significant long-term effect on energy use, a damper failure must increase building HVAC loads and/or reduce equipment efficiency. If a damper failure significantly affect the system's ability to deliver conditioning, however, the failure will likely result in a complaint call and often lead to problem resolution. For example, unwanted closure of a smoke damper would not likely affect energy use, because it would prevent space conditioning, causing occupant discomfort that probably would lead to a service call and problem resolution.

Table 8-9 illustrates the way that various damper failures can contribute to energy waste and provides estimates of each one's potential energy impact. Economizer failure has the greatest energy impact of all potential damper failure faults. On the other hand, most of the other types of dampers would primarily affect comfort, and are thus likely be repaired prior to causing significant energy waste. Economizers also have very high susceptibility to failure due to their exposure to ambient conditions and ambient air, notably in rooftop units (which are located outdoors). Spring-return motors cause economizers to fail shut when the motors fail, which prevents economizing but saves energy by eliminating the outdoor air intake. This applies, however, only to motor-related economizer failures.

Table 8-9: Damper Failure and Associated Energy Waste

Damper Type	**Economizer or OA/RA Mixing**	**VAV Valves**	**Dual-Duct or Multizone Mixing**	**Face/Bypass**	**VAV Bypass, Blower Throttling**
Affected Systems	Ducted units	VAV Units	Dual-Duct Units	Units with face/bypass heating or cooling control	Units with these modes of VAV control
Floorspace Affected [%]	32% of all Floorspace Note A	20% Note E	<2%	<10%	<10%
Energy Use [quads]	Cooling: 0.50 Heating: 0.35 Note B	Cooling: 0.28 Note E Fans: 0.14			Cooling: <0.14 Fans: <0.07
Energy Waste Mode(s)	Economizer fails to work to provide free cooling when available; Economizer fails open, causing excess outdoor air conditioning load.	Failure open can cause excess reheat and/or excess duct pressure setpoint (if duct pressure is reset based on valve position). Failure closed could cause manual reduction in supply air setpoint.	Improper control causes simultaneous heating and cooling for individual zone.	Poor control causing cyclic heating/cooling; manual reduction of chilled water temperature to compensate for poor F/B damper control	Failure to modulate air flow increasing blower power and cooling/reheat energy use.
Failure Prevalence	25 – 40% Note C	Unclear	Unclear	Unclear	Unclear
Energy Waste [%]	10 – 30% Note D	Low Note F	Unclear	8% Note J	Unclear
Energy Waste [quads]	0.02 – 0.1	(low)	(low) Note G	(low) Note H	(low) Note I

Notes

A: Source – EIA (1999)

B: The 32% of floorspace served by economizer represents 40% of floorspace served by packaged units and central systems. Energy use indicated equals 40% of energy used for heating and cooling for packaged units and central systems.

C: Based on literature reporting economizer failure, see relevant Energy Impact Table in Appendix E

D: Ranges of estimates for energy savings for properly-functioning economizers are from 2% to 40% (Financial Times Energy 2002; Davis et al. 2002a). Ranges of energy waste for cooling season up to 50% of cooling season energy assuming 100% of system air flow for economizer operation (Financial Times Energy 2002). A better understanding of actual energy wasted in the field is needed; however, energy waste representing 20% of energy use is considered a reasonable estimate of average waste for economizer failures.

E: EIA (1999) indicates that buildings with VAV systems represent 29% of floorspace. ADL (1999) segmentation calculations (based on EIA 1995) indicate that 11% of *heated or cooled* floorspace is served by central systems with VAV units. The 20% estimate acknowledges that many packaged units utilize VAV. Affected energy use equals 20% of 1.4 quads used for cooling and of 0.7quads used for supply/return fans.

F: Individual VAV valve failures would, in most cases, lead to poor space temperature control and subsequent problem resolution.

G: Limited overall use of dual-duct or similar systems. Data of Briggs et al. (1987) suggest that 7% of office space was served by Multizone or Dual Duct systems at the time of the reference. The prevalence of such systems likely has decreased significantly now for the entire building stock, due to the recognized inefficiency of this system type (Sezgen et al. 1995).

H: Low overall use of face/bypass coil control (This approach is used for heating coils to prevent freeze and for cooling coils, particularly of unit ventilators in classrooms, to improve latent performance at part load), limited scenarios for which energy use would increase rather than comfort be compromised.

I: Low overall use of VAV systems with these control approaches, and failure of these systems would likely result in sufficient comfort problems to have reasonable probability of detection and repair.

J: Increase in ventilation energy consumption, based on DOE 2.2 S simulations of a 105kft^2 office building in California with a VAV system (Eley Associates 2002).

The available data show that economizers have a high susceptibility to damage and waste the most energy waste of all dampers used in HVAC systems, i.e., likely between 10% and 30% (Barwig et al. 2002, Davis et al. 2002, TIAX 2002, Financial Times Energy 2003). Furthermore, a very large percentage (at least 35%) of economizer dampers of rooftop units fail within a few years of installation (from numerous sources cited in the Energy Impact Table, including: Rojeski and Groover 1998, Consortium for Energy Efficiency, Davis et al. 2002, Jacobs et al. 2003, Goody et al. 2003, Financial Times Energy 2003). Failure rates for central system air-handling unit economizer dampers are likely to be less prevalent. National energy waste resulting from damper failures lies between 0.02 and 0.1 quads. Efforts by manufacturers to increase the reliability of economizers, e.g., by using direct-drive geared motors to eliminate linkages, may decrease the incidence of certain types of damper faults in the future.

8.5.3 Quality of Existing Data

While several studies have quantified the prevalence of economizer failure in rooftop units, very few data are available regarding failure rates of economizers in central system air-handling units, and failure rates of other damper types.

Table 8-10: Data Gaps and Possible Solutions Dampers Not Working

Data Issue	Potential Solution(s)
Most data focus on rooftop unit economizers	Investigate economizers in central system air-handling units. Investigate failure of other types of dampers.
Incomplete categorization of modes of economizer damper failure (i.e., percent failing open versus closed) hampers better estimate of energy waste.	Field survey work focus on type of failure modes.
Incomplete understanding of energy impact of economizer failures.	Analysis to assess the impact of different modes of damper failure on heating and cooling energy use for different locations and building types.
Incomplete understanding of floorspace served by economizers in commercial buildings, particularly for different HVAC system types.	Modification of future CBECS surveys to look more closely at this issue.

8.6 Air Flow Not Balanced

Table 8-11: Summary of Air Flow Not Balanced

Characteristic	Result	Comments
Systems Impacted by Technology	All systems which condition a space by delivering heated and/or cooled air.	
Niches of High Fault Impact	Light commercial buildings Buildings undergoing frequent occupancy changes and construction modifications.	• Rarely commissioned, detection of problems less likely • Re-balancing to reflect altered space conditions may not be carried out.
Relevant Primary Energy Consumption (quads)	3.1	All HVAC energy associated with ducted central and packaged HVAC systems.
Prevalence of Fault	25% to 50%	Fault prevalence depends on degree of flow imbalance. Prevalence estimate applies to systems/buildings in which imbalance significantly affects comfort or energy use.
Energy Impact of Fault	2% to 10%	Rough estimate based on limited data.
National Energy Impact of Fault [quads]	0.02 to 0.16	Calculation based on relevant quads, prevalence and energy impact ranges
Data Gaps	Little quantitative data regarding prevalence of specific air flow balance problems and their energy impact.	
Can Diagnostics Address this Issue?	To some extent, yes. CO_2 measurements (e.g., for demand-controlled ventilation; see Section 9.3) could help infer insufficient airflow to a zone, measures described in the summary table for Section 8.7 could detect insufficient airflow to vapor compression cycles. More thorough balancing, e.g., adjusting fan performance as well as dampers, would reduce the frequency and intensity of this fault.	

8.6.1 Fault Overview

Air flow imbalances can lead to energy waste in several ways:

- Reduced air flow in a unitary system leads to lower evaporating temperatures, since most of units have constant-speed compressors. Lower evaporator temperatures, in turn, decrease compressor capacity and EER, which increases compressor energy consumption.

- Imbalance in air flow between zones served by a unit can cause some of the zones to not receive enough cooling. Energy waste depends on the operator's response to such a scenario. If the operator decreases the unit's supply air temperature setpoint to compensate, energy use for cooling will increase. In addition, reheat energy use to prevent overcooling of other zones may also result, although this effect would be mitigated for a VAV unit. The operator may also decrease chilled water temperature setpoints, thus reducing chiller efficiency.
- Excessive balance damper throttling and/or excessive air delivery results in excess supply and/or return fan energy consumption.
- Excessive outdoor air delivery can significantly increase cooling and heating loads.
- Negative and/or uncontrolled indoor pressure can cause excessive infiltration, which increases the conditioning load while reducing occupant comfort.

Unbalanced air systems can also create non-energy problems. Some buildings, such as hospitals and health facilities, require proper air flow patterns to prevent the spread of disease or prevent odors or excessive humidity from entering other spaces. Excessive negative pressure in humid climates has caused moisture to infiltrate the building shell, leading to mold growth and costly damage. Unbalanced systems can also reduce the quantity of outdoor air (OA) reaching building zones, which reduces the energy consumed to condition the OA but could cause the zone to not satisfy minimum OA levels specified by ASHRAE Standard 62.

Many potential reasons for air balance problems exist, such as poor design, an absence or incomplete testing and balancing (T&B) work, difficulties in implementing design intent due to high system complexity, system modifications made after T&B work, changes within space loads without reconsideration of air flow and system capacity, etc. The literature describing air flow balance issues, however, often does not identify the relative importance of each of these factors.

8.6.2 Fault Energy Impact

Energy Impact Data tables (see Appendix E) summarize the literature containing information about the prevalence and energy use impact of air flow balance issues, respectively. One entry provides an indication of the potential magnitude of energy waste that could result from poor air balance: 5,520kWh and 282 therms per year in a 23,000ft^2 existing building (SBW Consulting 2003). This represents annual primary energy waste of about 3.9kBtu/ft^2, or about 5% of the roughly 80kBtu/ft^2 average HVAC primary energy use in U.S. commercial buildings[88]. While this provides a reasonable order of magnitude of the potential energy waste associated with poor air flow balance, a lack of quantifiable data

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[88] Primary energy use of major fuels in commercial buildings equals: 9.4 quad electricity, 2.0 quad natural gas, 0.18 quad fuel oil, and 0.43 quad district heating, for 67.3 billion sqft floorspace (EIA 1999).

supporting prevalence of specific air flow balance issues impairs development of the actual national energy impact.

The very limited data available indicate that air flow balance problems can occur in a range of building types and system types and can increase HVAC energy consumption by on the order of 5%. Further quantitative data are required to develop a better estimate of the actual national energy impact.

8.6.3 Quality of Existing Data

Although the literature contains several sources of anecdotal information regarding the existence of air flow balance problems in commercial buildings, little quantitative data exists about the prevalence of significant issues and the range of the associated energy waste.

Table 8-12: Data Gaps and Possible Solutions Air Flow Not Balanced

Data Issue	Potential Solution(s)
Limited understanding of the energy impact and relative importance of specific air balance problems.	• Analytical modeling (e.g., EnergyPlus) to estimate the potential impact. • Focused search for better energy impact data collected by ESCOs or commissioning companies.
Lack of quantification of the number of buildings which have significant air balance issues.	Building surveys with a greater focus on this issue and its quantification.

8.7 Insufficient Evaporator Airflow

Table 8-13: Insufficient Evaporator Airflow

Characteristic	Result	Comments
Systems Impacted by Technology	All cooling systems and heat pump-based heating systems	
Niches of High Fault Impact	Unclear	• Primary research focus suggests smaller air-conditioning units
Relevant Primary Energy Consumption (quads)	1.5	All cooling energy consumption and associated parasitics
Prevalence of Fault	15%-40%	For rooftop A/C, based on <300 cfm/ton threshold
Energy Impact of Fault	4-13%	Range reflects ~300cfm impact values of ~4% (Parker et al. 1997; Davis et al. 2002) and 13% (Breuker and Braun 1998)
National Energy Impact of Fault [quads]	0.009 – 0.08	Calculation based on relevant quads, prevalence and energy impact ranges
Major Data Gaps	• No data available for central systems, very limited data for larger RTUs • Difficult to determine prevalence of specific problems responsible for reduced evaporator airflow, i.e., coil fouling, clogged filters, duct design, etc. • Design airflows not known for units evaluated in field studies • Large variance in EER impact of different airflow levels in literature	

Characteristic	Result	Comments
Can Diagnostics Address this Issue?	Yes – on-site diagnostics exist, including TrueFlow (airside pressure drop over coil), CheckMe (sensible capacity to moisture removal balance). Airside filter differential pressure measurements are common for RTUs and central systems. Alternatively, systems could use filters that prevent substantial fouling or clogging of the evaporator, i.e., that capture a higher portion of particulates.	

8.7.1 Fault Overview

Damaged, dirty, or clogged cooling coils and filters reduce the airflow over the cooling coil and compromise the heat transfer effectiveness of the evaporator. Dust and other particulates can deposit on the cooling coil surface, which fouls the surface and can reduce the heat transfer effectiveness of the evaporator. Cooling coil fouling appears, however, to be more likely to reduce airflow than filter clogging (Carl and Smilie 1992), perhaps because it is generally easier to maintain/change a filter than a cooling coil. Air leaks around the filters also occur, especially when clogged filters are not replaced, allowing dust to land on coil surfaces. Improper duct design (e.g., high duct pressure drop), low blower speed, and dirty blower wheels can also reduce evaporator airflow. In many systems, insufficient evaporator airflow can also be associated with insufficient outdoor air (OA).

A decrease in evaporator airflow below design levels will shift the balance towards greater moisture removal. Decreased evaporator airflow or evaporator fouling decreases the refrigerant saturation temperature at the evaporator, which increases the temperature lift of the vapor compression cycle. The net result is a decrease in both system cooling capacity and cycle COP. Extremely low airflow levels (e.g., <50% of recommended levels; Parker 1997) may freeze the cooling coil and cause refrigerant floodback that can damage the compressor (Hewett et al. 1992; Parker et al. 1997; Breuker and Braun 1998).

8.7.2 Fault Energy Impact

The Energy Impact Data (see Appendix D) show that many commercial A/C systems have lower than optimum cooling coil airflow. Some references site a “proper” cooling coil airflow of 400 cfm per ton of refrigeration (Architectural Energy 2003, Davis et al. 2002; Hewett et al. 1992) that provides a comfortable balance between moisture removal and sensible cooling. Although this may be the case for some units located in regions with low humidity, 400 cfm/ton does not represent a universal optimum per-ton volume flow rate from an efficiency point of view. Indeed, some packaged rooftop unit designs purposefully use lower airflow levels to achieve *higher* EER ratings with increased dehumidification factor (sensible heat ratio), as lower airflow volumes reduce blower power consumption for a CAV unit. The overall impact of a specific level of evaporator airflow on total HVAC energy consumption in an actual system depends on the relative size of total system energy consumption accounted for by the blower and the compressor. Blower energy, in turn, depends on the actual duct design. These factors likely explain some of the scatter for the energy impact differences between sources (e.g., Breuker and Braun 1998, Parker et al. 1997).

Surveys of commercial A/C units found that the average evaporator airflow varied from 304 cfm/ton to 334 cfm/ton, equal to 16.5% to 25% less than the 400 cfm/ton “optimum.” Most of these studies were performed in units deployed on the West Coat of the U.S., a region where, conceivably, units might operate at higher cfm/ton values because of modest latent loads. The actual optimum cfm/ton values for these units were not, however, known. Taking into account that small drops in airflow have a minor effect on efficiency and capacity and assuming that: a) 400 cfm/ton does represent an optimum airflow for the units evaluated and b) units across the nation that exhibit optimum operation at lower cfm/ton values suffer similar *percentage* degratdations, it appears that at least 25% of packaged RTUs have a fault sufficient to have an energy impact of about 5% or greater (Hewett 1992, Breuker and Braun 1998, Davis et al. 2002, Downey and Proctor 2002, Architectural Energy 2003, Rossi 2004). Based on these assumptions, the national energy waste of insufficient evaporator airflow ranges from 0.009 to 0.08 quads.

8.7.3 Quality of Existing Data

Almost all of the existing data focus on RTUs and residential split systems. Presumably, larger RTUs and central systems are better maintained than light commercial RTUs, but not enough data exist to confirm this assumption. In addition, the design airflows of the units evaluated in field studies were not known but assumed to be 400 cfm/ton; in practice, many units have appreciably lower design airflows.

Table 8-14: Data Gaps and Possible Solutions – Insufficient Evaporator Airflow

Data Issue	Potential Solution(s)
Negligible data for systems, e.g., central, other than small RTUs	Measure airflow levels (cfm/ton) and SEER impact in central systems and larger RTUs
Significant variances in estimates for the EER impact of different levels of low airflow	Analytical evaluation of how low airflow levels impact EER of larger (5+ ton) RTU and central systems, taking into account actual system and equipment designs
Optimum evaporator airflow not known for units evaluated in field studies	Record model numbers and find out design evaporator airflow from unit specifications
Incomplete understanding of reasons for insufficient evaporator airflow	Field survey work to develop information about the distribution of root causes

Another, smaller issue, is that the literature offers conflicting views on the relative pressure drops of flat and pleated filters. Similarly, it is not clear that filter selection recommendations prevent substantial fouling or clogging of the evaporator while providing a cost-effective balance between preventing (and saving energy) evaporator fouling and filter maintenance cost (change interval and filter cost).

8.8 Software Programming Errors

Table 8-15: Summary of Software Programming Errors

Characteristic	Result	Comments
Systems Impacted by Technology	Systems with electronic controls or Energy Management and Control Systems (EMCS) that perform active control functions.	
Niches of High Fault Impact	Buildings with complex, centrally controlled systems	• Limited electronic control use for packaged and individual systems. The simpler control schemes and lack of operator software modification also makes these systems less susceptible to software errors. • Central systems with complex and custom-developed control algorithms to optimize energy use have the greatest susceptible to errors.
Relevant Primary Energy Consumption (quads)	1.1 2.9	Heating, cooling, and thermal distribution of central systems. Heating, cooling, and thermal distribution for all other systems.
Prevalence of Fault	10 to 30%	Estimate applies to central systems. Assume that software errors in non-central systems currently cause insignificant energy waste.
Energy Impact of Fault	1 to 10%	Estimate applies to central systems. Assume that software errors in non-central systems currently cause insignificant energy waste.
National Energy Impact of Fault [quads]	0.001 to 0.03	Based on central systems
Data Gaps	• Trends in use of electronic controls in different types of HVAC equipment. • More statistically-based understanding of the prevalence of software and programming errors and their energy impact.	
Can Diagnostics Address this Issue?	Yes. Trend analysis can detect some problems caused by software programming errors. However, proper commissioning of EMCS and training of operators may be a more cost-effective approach.	

8.8.1 Fault Overview

Any control system that incorporates electronic control can, in theory, can waste energy due to software errors. Traditionally, however, packaged and individual air-conditioning units have rarely used electronic controls. Furthermore, electronic controls supplied with these types of units are less likely to have software issues because they perform simpler control functions and carry out standardized control functions that are tested and validated during product development.

Software programming is part of the ECMS installation process. The control specifications, however, often were developed without knowledge of the controlled equipment and the full intent of the control sequences, which compromises control effectiveness. This decreases the efficacy of building controls (Hartman 2000). Many of the literature-reported control software issues are associated with Energy Management and Control Systems (EMCS) that actively control and monitor system behavior. Control problems with such systems were studied in depth by Ardehali and Smith (2002; see the Appendix to this subsection), who cataloged several programming problems that arose in prior studies, including:

- Improper setpoint or schedule;
- Improper control logic;
- Improper operation of equipment, and
- Improper operation of controlled device (e.g., VAV box, Damper, VFD, etc.).

Often, building operators have little or no training in how to operate the EMCS. This also prevents proper control system operation, which can lead to the system being disconnected.

While use of EMCS opens the door to implementation of more sophisticated control of HVAC systems, depending on the control system architecture, it also allows the operator to override key building settings (temperature setpoints, schedules, etc.) in response to complaint calls that can compromise the longer-term effectiveness and energy efficiency of building system control. In some cases, fault-driven interventions by building operators can lead them to believe that manual control of building systems is necessary for effective climate control (Hartman 2005b). This, in turn, can increase subpar building operations and building energy consumption. Section 8.3, "HVAC and Lighting Operating During Unoccupied Hours," addresses scheduling-related energy waste.

8.8.2 Fault Energy Impact

Overall, control-related problems may account for up to half of energy waste (i.e., Case Study 6 of Ardehali and Smith [2002], based on Herzog and Wheeler & Associates [1992]). Software programming errors reported in the literature are primarily associated with central systems. The prevalence of software errors found in the Ardehali and Smith (2002) study averaged just over 1 per building, while other sources show significantly higher software or programming errors (see the Energy Impact Table in Appendix E). The prevalence estimate assumes that 10% to 30% of buildings with central HVAC systems have an EMCS with software errors. The energy use impact associated specifically with programming errors is difficult to separate from other errors, e.g., many cases report the energy impact for a larger group of control system fixes. Furthermore, in many cases it is not clear whether a problem arose during initial system programming, controls set-up, or as a result of operator override. While the available data suggest a range of energy waste, it is difficult to "tighten" the range of the estimate.

The available data show that software programming errors have been the cause of a significant portion of HVAC system problems in studied buildings. Most of these errors are associated with EMCS or DDC control systems, more often than not in buildings with more complicated HVAC systems. In addition, a thorough commissioning processes would have identified most of the errors. Overall, the national energy impact of software and programming faults is difficult to estimate based on available data, i.e., very limited data suggest a wide range of from 0.001 to 0.03 quads.

8.8.3 Quality of Existing Data

Despite several references that provide a general indication of the prevalence of EMCS software programming problems and their potential energy impact, the literature does not offer meaningful correlations between specific problems and levels of energy use impact.

Table 8-16: Data Gaps and Possible Solutions for Software Programming Errors

Data Issue	Potential Solution(s)
No statistically based investigations of energy use impact	More systematic examination of existing data which often is not publicly available.
Energy use impact presented for groups of improvements rather than focusing on individual software issues	More careful reporting of commissioning and building survey work.

8.8.4 Appendix – Controls-Related Faults Assessment of Ardehali and Smith (2002) / Barwig et al. (2002)

Case studies and anecdotal accounts abound for the underlying reasons building controls do not realize their full energy savings potential. The literature review of Ardehali and Smith (2002) (also presented in Barwig et al. 2002), analyzed building controls problems from 67 case studies, encompassing 118 buildings. Based on the information available in the case studies, they categorized the primary causes of energy performance shortfalls (see Figure 8-3[89]). Insufficient information existed to quantify the energy impact of each problem in most cases.

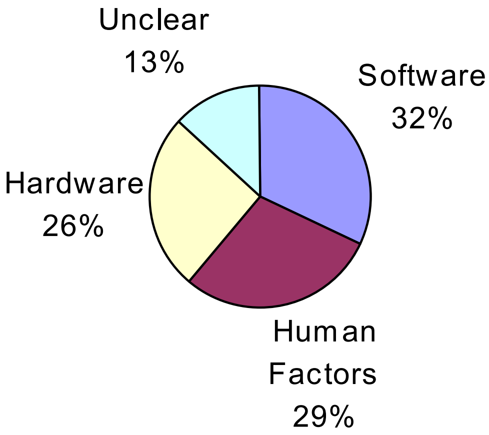

Figure 8-3: Primary Causes for EMCS Performance Shortfalls (from Ardehali and Smith 2002)

A related effort (Barwig et al. 2002) surveyed building controls industry experts in an attempt to develop a more refined assessment of building controls problems. At a top level, the survey results validate the primary problems identified in the literature survey; in

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[89] Ardehali and Smith (2002) indicate that "the majority of the non-specified problems reviewed .. include malfunction or improper operation of the economizer".

addition, they provided a qualitative estimate of the energy impact of different problems (see Table 8-17).

Table 8-17: Barriers Impeding EMCS Energy Savings and Operation, Ranked by Prevalence and Energy Impact (from Barwig et al. 2002)

Problem	Type	Description	Relative Prevalence	Relative Energy Impact
Input Device	Hardware	Sensors, transducers, wiring	High	High
Controller	Hardware	Controller hardware/component problems/failure	Low	Low
Controlled Device	Hardware	Valves and dampers (and their operators), electric relays, fans, pumps, compressors, VSDs	Medium	High
Communications	Hardware	Data transmission hardware	Low	Medium
I/O Implementation	Software	Problems with control software arising prior to building end user receipt of system (e.g., point addressing)	High	High
Programming	Software	Incorrect or inappropriate control logic	High	High
Operation	Software	Arise after building start-up (e.g., loss of setpoints from power outage)	Medium	Medium
Data Management	Software	Data monitoring, display, archiving, etc.	Low	Low
Operator Error	Human Factors	Unintentional changes to control system during system operation or maintenance	High	High
Operator Unawareness	Human Factors	Lack of operator understanding, operator ignorance	Medium	High
Operator Interference	Human Factors	Intentional modification of control systems	High	High
Operator Indifference	Human Factors	Operator apathy towards building system operation or maintenance	Low	Medium

8.9 Improper Controls Hardware Installation

Table 8-18: Summary of Improper Controls Hardware Installation

Characteristic	Result	Comments
Systems Impacted by Technology	All HVAC systems and larger refrigeration systems. To a lesser degree, lighting and water heating systems.	
Niches of High Fault Impact	Not clear	
Relevant Primary Energy Consumption (quads)	5.0	All HVAC and larger refrigeration systems
Prevalence of Fault	5% to 10%	Rough estimate
Energy Impact of Fault	0.5% to 5%	Rough estimate, percentage of all HVAC and larger refrigeration system energy use
National Energy Impact of Fault [quads]	0.0013 to 0.025	Calculation
Data Gaps	Very little data regarding prevalence of problems or of energy impact.	
Can Diagnostics Address this Issue?	Yes: Trends analysis can detect installation issues, but proper commissioning may be a more cost effective approach.	

8.9.1 Fault Overview

Improper or incomplete installation of control components accounts for a large portion of system problems identified in the literature. A wide range of installation issues appear to affect a range of equipment and system types, with improper sensor or thermostat location likely more common than other faults for EMCS-based systems (Ardehali and Smith 2002). Incorrect outdoor air temperature sensor placement, e.g., in the sun, can result in a 4^o to 7^oC error in temperature measurements (VTT 2001). While identification of reasons for these problems lies outside the scope of this study, one can surmise that improper installation occurs for several reasons, including underfunded installation work due to competitive bidding, poor installer training, weak or improper specifications (Santos and Brightbill 2002; Hartman 2000), insufficient product installation information, poor contractor oversight, and lack of commissioning. The effects of poor control hardware installation depend strongly on specific installation details. In many cases, improper equipment operation interferes with delivery of space conditioning and is addressed to maintain occupant comfort. When the faults have no direct impact on occupants, however, the installation faults tend to evade detection and persist. In all cases, installation faults may or may not lead to ongoing energy use increase.

8.9.2 Fault Energy Impact

While the literature reveals a number of surprising errors (see the Energy Imapct Table in Appendix E), it contains little solid information about the energy impact of these errors. Many of the identified errors would often cause comfort problems in the buildings (e.g., piping errors leading to chiller shutdown) that would lead to identification and repair rather than persistent, significant energy waste. Furthermore, initial commissioning studies of new and/or retrofit installations contain much of the useful data, which raises questions about developing valid extrapolations of the observed failure frequencies to the national building stock. Only one of the citations provides a direct energy cost estimate (~$0.012/$ft^2$; from Haasl et al. 1996). Another citation indicates that economizers do not function, a situation that might result in energy waste equal to 5% to 10% of cooling season energy in the California climate (Khan et al. 2002). The Ardehali and Smith (2002) literature review suggests that improper hardware installation in buildings with EMCS occurred at a rate of once every 7.3 buildings.

The data indicate that the most prevalent installation faults include miswiring of sensors or controlled components and poor placement of sensors. In many cases, however, the wrong components were installed and/or basic installation instructions clearly were not followed. Moreover, many of the installation faults would have been identified if a commissioning process were implemented. A rough estimate national energy impact based on the very limited data regarding the energy impact of poor installation suggests that improper controls hardware installation increases annual energy consumption by between 0.0013 to 0.025 quads.

8.9.3 Quality of Existing Data

As noted in the prior section, very little information exists about the energy impact of installation faults. Also, most of the existing data for prevalence come from commissioning studies of building retrofits and new construction, which may not offer a representative picture of the existing building stock.

Table 8-19: Data Gaps and Possible Solutions for Improper Controls Hardware Installation

Data Issue	Potential Solution(s)
Most available information is from the perspective of commissioning of a new or retrofit installation and provides little insight about the prevalence in existing buildings and/or possible energy use impact.	More focused surveys of existing buildings
Very little information about fault energy impact	Simple tools to simulate the energy impact of controls-related faults

8.10 Improper Controls Set Up or Commissioning

Table 8-20: Summary of Improper Controls Set Up or Commissioning

Characteristic	Result	Comments
Systems Impacted by Technology	All HVAC systems. To a lesser degree, lighting and water heating systems.	
Niches of High Fault Impact	Buildings with Central HVAC Systems	The higher complexity of central systems requires more control adjustment to achieve optimum performance.
Relevant Primary Energy Consumption (quads)	5.0	HVAC and Larger Refrigeration Systems
Prevalence of Fault	5 to 25%	Rough estimate
Energy Impact of Fault	1 to 5%	Rough estimate
National Energy Impact of Fault [quads]	0.0025 to 0.06	Calculation based on relevant quads, prevalence and energy impact ranges
Data Gaps	• Very little data regarding prevalence of problems. • Insufficient data on energy impact to draw robust conclusions.	
Can Diagnostics Address this Issue?	Unclear: Trends analysis would not be likely to identify problems in an improperly set up system. Commissioning or Development of easier to set up or self-configuring control systems may be the best approach to reduce the frequency of this problem.	

8.10.1 Fault Overview

Many control systems for commercial building HVAC systems require some level of "configuration" after installation of the hardware, such as:

- Establishing equipment operating schedules;
- Establishing system operating setpoints (AC unit supply temperature, chilled water temperature, etc.);
- Selection of equipment operating temperature ranges (e.g., chillers operate only when outdoor temperature exceeds 55°F, economizer operative below 60°F)
- Selection of control parameter coefficients for control loops, for instance, PID coefficients;
- Establishing reset schedules for: (a) duct pressure control for VAV systems, (b) chilled water or heating water temperature, (c) AC unit supply temperature, etc., and
- Position of mixing dampers for minimum outdoor air delivery.

HVAC systems cannot run at optimum efficiency levels with inappropriate adjustment of parameters and establishment of setpoints for a given building. Many faults identified in the literature arise from poorly configured control systems that either do not provide adequate space conditioning or ventilation, or leads to excessive energy use. In more extreme cases, the control system is not configured at all.

Optimization of controls often demands operation of the system and associated equipment, observation of system performance, and making adjustments based on those observations. It may even require observation of system performance during different seasons and/or diverse space occupancy patterns. Consequently, it may not be possible to achieve adequate – let along perfect – system configuration upon system installation. Optimization in such cases may become part of a commissioning process or part of a retro-commissioning or continuous commissioning activity.

This section does not consider the energy impact from improp equipment operating schedules for lighting and HVAC systems; Section 8.3 discusses HVAC and lighting operation during unoccupied hours separately.

8.10.2 Fault Energy Impact

Several literature sources provide estimates of energy use reduction associated with optimization and/or elimination of control set-up issues (see Appendix E). Most of the citations that provide quantitative information on energy or energy cost savings show relatively modest gains on the order of no more than a few cents per square foot of floorspace, perhaps as large as a few percent of total HVAC system energy consumption. The ongoing commissioning efforts performed by Texas A&M researchers are notable exceptions (Claridge et al., 1994 and 2000, and Liu et al., 1993a, 1993b, 1993c, and 1994). In contrast to other studies, they reported energy cost savings ranging from roughly \$0.40/ft^2 to \$1.20 ft^2, compared with a national average energy cost of \$1.21/ft^2 for all commercial building energy (EIA 1999). The buildings in question do not appear to be representative of the national commercial building stock: their baseline energy use for HVAC (not including electricity for fans, blowers, and pumps located within the buildings) ranged from 231 to 323kBtu/ft^2 compared to a commercial building national average energy use intensity of 178kBtu/sqft for *all* energy uses (EIA 1999). They also explicitly considered buildings suspected to have excessive energy use and strove to not only remedy subpar operation but to “optimize the HVAC system operation and control to minimize building energy consumption” (Liu et al. 2003). Considering the broader literature, setup errors likely increase the energy consumed by all pertinent end-uses by a range of 1% to 5%.

Beyond improperly established equipment operating schedules for lighting and HVAC systems, which are analyzed separated in Section 8.3, the most wasteful problems discussed in the literature involve simultaneous heating and cooling, particularly of dual-duct systems. Over the years, the use of these types of systems has declined, due to their recognized poor energy efficiency. In cases where these systems are used, control approaches that reduce their energy waste are implemented, such as variable air volume and avoidance of simultaneous operation of both the heating and cooling coils.

8.10.3 Quality of Existing Data

This fault suffers from major data gaps on all fronts.

Table 8-21: Data Gaps and Possible Solutions for of Improper Controls Set Up or Commissioning

Data Issue	Potential Solution(s)
Very little good data regarding prevalence of this problem	More systematic survey work.
Insufficient data to ascertain key sub faults	More systematic survey work.
Insufficient data on energy use impact to draw statistically robust conclusions regarding national energy impact a	More systematic survey work. Analysis addressing this issue, e.g., development of a simple tool to assess the energy impact of different control strategies

8.11 Control Component Failure or Degradation

Table 8-22: Summary of Control Component Failure or Degradation

Characteristic	Result	Comments
Systems Impacted by Technology	All HVAC systems and larger refrigeration systems. To a lesser degree, lighting and water heating systems.	
Niches of High Fault Impact	No	All systems appear to have similar frequencies of control component degradation. Simpler HVAC systems in smaller buildings may receive less attention, but failures in smaller buildings would be less likely to affect energy use because of their simplicity.
Relevant Primary Energy Consumption (quads)	5.0	HVAC and larger refrigeration energy use.
Prevalence of Fault	5 to 25%	Rough estimate
Energy Impact of Fault	1 to 5%	Rough estimate
National Energy Impact of Fault [quads]	0.0025 to 0.06	Calculation based on relevant quads, prevalence and energy impact ranges
Data Gaps	• Very little prevalence data • Insufficient data on energy impact to draw robust conclusions.	
Can Diagnostics Address this Issue?	Yes. Monitoring systems should be able to detect changes in system operation resulting from control system degradation and sensor drift.	

8.11.1 Fault Overview

Controls components do fail, which decreases control system functionality. For example, sensors fall out of calibration and provide inaccurate input to controllers. Valve and damper actuators can wear out, which prevents a controller from effectively adjusting equipment operation in response to changing conditions. Controllers themselves can fail. While the fact of control degradation is not surprising, little attention is paid to ongoing verification that control systems continue to operate as intended.

As with other HVAC system failures, the energy use impact of control component degradation depends on the system details. Loss of calibration of space temperature sensors generally leads to adjustment of setpoints and little change in space temperature levels. When a supply air or chilled water temperature sensor drifts out of calibration, the air or chilled water temperature increases or decreases. In this case, the building operator or tenants often will not notice the problem because it may not affect comfort. Because the fault is not noticed and fixed, energy use often increases.

8.11.2 Fault Energy Impact

The literature review of Ardehali and Smith (2002) found that the rate of sensor or thermostat failure for buildings with EMCS averages about one failure for every two buildings. However, many of the other citations seem to indicate rates of failure of control components higher than this (see Appendix E). Dampers, valves, controllers, and variable-frequency drives (VFDs) also had high malfunctioning rates (sub-sections 8.5 and 8.12 discuss damper and valve problems, respectively). Some sources provide information about the energy use impact associated with control component failure, but it covers a very broad range (negligible to close to $1/ft^2). The high-end estimate comes from a building with a baseline energy cost of $7/ft^2, which far exceeds the national average cost for commercial buildings of $1.21/ft^2 (EIA 1999). While in limited cases very high levels of energy waste result from control degradations, energy waste more typically equals pennies per square foot per year. Thus, a reasonable range of energy impact for control degradation, including loss of calibration, is 1% to 5% of HVAC energy consumption.

8.11.3 Quality of Existing Data

As with several of the controls-related faults, “Control Component Failure or Degradation” has large uncertainties in both its prevalence and energy impact

Table 8-23: Data Gaps and Possible Solutions for Control Component Failure or Degradation

Data Issue	Potential Solution(s)
Very little prevalence and energy impact data to draw robust national energy impact conclusions	More systematic survey work for prevalence; analysis of more common and higher-impact problems for energy impact

8.12 Valve Leakage

Table 8-24: Summary of Valve Leakage

Characteristic	Result	Comments
Systems Impacted by Technology	All systems which have thermal distribution in piping systems: steam piping, heating water piping, chilled water piping, water heating piping.	
Niches of High Fault Impact	Old steam systems	Steam valves and traps require occasional repair-monitoring to detect failures and prevent significant system losses from valve leakage.
Relevant Primary Energy Consumption (quads)	0.8	Heating and cooling of central systems (boilers and chillers)
Prevalence of Fault	5 to 25%	Rough estimate
Energy Impact of Fault	1 to 10%	Rough estimate
National Energy Impact of Fault [quads]	0.0004 to 0.02	Calculation based on relevant quads, prevalence and energy impact ranges
Data Gaps	Very little data regarding prevalence of problems or of energy impact.	
Can Diagnostics Address this Issue?	Yes: Well-placed temperature sensors combined with appropriate logic algorithms could detect valve leakage; cost a concern, due to a significant increase in the number of required sensors, wiring, and I/O. Trends analysis can also detect valve leakage, e.g., to note high levels of steam flow on a mild day.	

8.12.1 Fault Overview

Valve leakage primarily affects control valves, shutoff valves, and steam traps. Control valves modulate the fluid flow through heating and cooling coils (steam, heating water, and chilled water). Shutoff valves stop the flow to thermal distribution systems, particularly for steam systems. Steam traps allow condensed steam from a steam loop to drain from the distribution system to the boiler while preventing the flow of live steam to the condensate collection tanks. Live steam that enters the condensate return system is generally vented from condensate collection tanks, which wastes the steam’s useful heating content. Several mechanisms can lead to valve leakage when the valve is in the closed position, including excessive throttling near the vale seat that causes erosion of the seat.

8.12.2 Fault Energy Impact

Energy waste associated with valve leakage depends on the particular failure scenario. In some cases, leakage past a closed valve has little impact. For instance, leaky valves cannot waste energy during periods when the chilled water system is shut down because the building does not require cooling. Energy waste is most likely to occur in buildings with diverse needs for a given thermal system. For instance, a steam system may operate year-round to supply steam to domestic water heaters. In this case, live steam can leak through valves and provide preheating throughout the cooling season. If the steam distribution system has separate supply headers for different service needs, this offers the possibility to shut off certain loads via main shutoff valves to reduce the possibility of steam leakage. Each building has different design details and, consequently, a different probability that a leaking valve will waste energy. Overall, Energy waste primarily associated with shutoff valves, control valve, and steam traps. The greatest potential for energy waste occurs in steam systems.

Data derived from the literature provide some basis for estimating the possible magnitude of valve leakage energy waste. Specific examples listed in Appendix E indicate that valve leakage can increase energy costs from \$0.03 to \$0.07/ft^2; this compares with overall U.S. commercial building energy costs of \$1.21/ft^2 (EIA 1999). This indicates that energy waste associated with leaky valves can represent on the order of 5% of building energy cost. The data do not, however, provide enough quantification of the prevalence of the problem to develop a solid estimate of the national energy impact. A preliminary estimate is that substantial valve leakage may occur in between 5% and 25% of buildings with central systems and increase HVAC energy consumption by 1 to 10%.

8.12.3 Quality of Existing Data

The literature offers some data that provides a rough estimate for the range of valve leakage problems that occur in commercial buildings and gives some insight regarding the general range of the national energy impact. More quantitative data would help to clarify the cost-effectiveness of widespread *in situ* diagnostics for different applications.

Table 8-25: Data Gaps and Possible Solutions for Valve Leakage

Data Issue	Potential Solution(s)
No survey data to provide accurate assessment of valve leakage prevalence	• More systematic survey work.
Incomplete understanding of the range of possible energy waste associated with valve leakage.	• More systematic survey work. • Analysis to model the energy impact of key faults.

8.13 Air-Cooled Condenser Fouling

Table 8-26: Summary of Air-Cooled Condenser Fouling

Characteristic	Result	Comments
Systems Impacted by Technology	All systems which use air-cooled condensers, notably rooftop units (RTUs), air-cooled chillers, and commercial refrigeration (supermarkets, restaurants)	
Niches of High Fault Impact	Light commercial buildings using rooftop AC units	Detection of problems less likely
Relevant Primary Energy Consumption (quads)	1.5	Rooftop units account for about half of cooling energy consumption, commercial refrigeration about 1/3rd
Prevalence of Fault	Approximately 5-10%	
Energy Impact of Fault	6-8%	Average based on field measurements and laboratory testing
National Energy Impact of Fault [quads]	0.004 – 0.012	Calculation based on relevant quads, prevalence and energy impact ranges
Major Data Gaps	• Limited understanding of extent and prevalence of fault. • Limited condenser fouling data primarily for rooftop units in a few geographic locations	
Can Diagnostics Address this Issue?	Yes –see Section 9.8	

8.13.1 Fault Overview

Air-cooled condensers foul when outdoor particulates deposit on the condenser coil surface. Seasonal fouling occurs in many parts of the country, due to large releases of pollen in spring and the falling of leave in autumn. Fouling, as well as bent or damaged coil fins, reduces the air flow rate over the condenser coil, which leads to higher condensing pressures that increase compressor power draw and can also reduce compressor life. High levels of fouling may also cause liquid floodback, i.e., liquid passing through the evaporator into the suction line to the compressor, which can cause severe compressor damage (Breuker and Braun 1998a). Condensers, particularly those located near salt water, can suffer from corrosion that attacks and corrodes the coil materials, which can cause the fin area to decrease (e.g., from losing fins). This does not reduce condenser airflow but can reduce the coil area and lead to higher condensing pressures.

8.13.2 Fault Energy Impact

Condenser fouling appears to have the greatest national energy impact in packaged RTUs installed on light commercial buildings for two reasons. First, packaged RTUs account for about 60% of commercial building cooling energy consumption. Second, these units tend to receive little maintenance because they are inconvenient to access for maintenance and inspection. Without regular maintenance, condenser fouling problems may develop over and persist for extended periods. Because building occupants focus on comfort rather than efficient operation, a condenser fouling-related service call will normally only occur when conditioned space comfort has been noticeably affected, i.e. after extensive fouling.

Nationally, between 5% and 10% of rooftop units appear to suffer from condenser fouling, often due to lack of maintenance (Davis et al. 2002, Goody et al. 2003, Rossi 2004). High levels of condenser fouling result in relatively moderate decreases in refrigeration capacity reduction while decreasing COP to a greater extent. For example, a 56% blockage (by area) of the condenser coil area decreases refrigeration capacity by 11% and COP by 18% in a 3-ton unit (Breuker and Braun 1998a). National energy waste resulting from condenser fouling ranges from 0.004 to 0.012 quads.

8.13.3 Quality of Existing Data

Very little information exists about the extent and prevalence of fouling and that which exists focuses almost exclusively on RTUs. Negligible information is available for other equipment types such as chillers, heat pumps, commercial refrigeration, PTACs, and RACs. Prior studies also were primarily conducted on the west coast, further increasing the uncertainty of national fault prevalence and impact.

Table 8-27: Data Gaps and Possible Solutions Air-Cooled Condenser Fouling

Data Issue	Potential Solution(s)
Very limited data for rooftop units. Negligible data for other systems.	Investigate effect, prevalence, and extent of fouling in air-cooled chillers, commercial refrigeration, PTACs, heat pumps, and RACs.
Incomplete understanding of extent and prevalence of fouling.	Field survey work in various geographic locations to encompass range of condenser conditions, i.e. dusty, salt-laden, moist, etc.
No widely-adopted cost-effective *installed* diagnostic for detecting condenser fouling	Development of cost-effective diagnostic for condenser fouling, e.g. pressure and temperature measurements of refrigerant entering and leaving condenser coil (e.g., per Breuker and Braun 1998b; Braun 2003)

8.14 Improper Refrigerant Charge

Table 8-28: Summary of Improper Refrigerant Charge

Characteristic	Result	Comments
Systems Impacted by Technology	All vapor-compression cycles	
Niches of High Fault Impact	Smaller RTUs	• Detection of problems less likely than in chillers and supermarket refrigeration systems – less maintenance and monitoring, and no refrigerant receiver
Relevant Primary Energy Consumption (quads)	1.8	All cooling and refrigeration/freezer (supermarket and walk-in) energy except absorption chillers
Prevalence of Fault	40 – 80%	For packaged RTUs; likely much lower for larger systems (chillers and supermarket refrigeration systems)
Energy Impact of Fault	5 – 15%	Primarily for packaged RTUs and smaller units
National Energy Impact of Fault [quads]	0.02 – 0.12	Energy impact assessed only to packaged RTU, RAC, PTAC, and heat pump energy consumption (~1.05 quad total; ~0.95 quad cooling)
Major Data Gaps	• Prevalence-extent probability distribution • Data for larger unitary equipment and chillers	
Can Diagnostics Address this Issue?	Yes – See Section 9.8. In addition, thermostatic expansion valves (TXVs) can mitigate the impact of modest deviations from design charge level.	

8.14.1 Fault Overview

Improper refrigerant charge occurs in vapor compression (VC) cycles because refrigerant leaks out of the system or because of improper system charging when it is installed or serviced. Common reasons for refrigerant leaks include poorly made brazed joints, inadequate attention to sealing threaded joints, fatigue of piping components, and inherent leakage of components such as open-drive compressors and automotive-style refrigerant hose[90]. If a leaking unit does not receive maintenance, the charge level gradually decreases.

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[90] Note that these two specific examples are uncommon in packaged RTUs.

The first sign of a refrigerant leak on an unmaintained unit often will be the inability of the unit to meet the cooling load on a hot day. Overcharge, on the other hand, usually occurs during unit maintenance, i.e., the technician puts too much refrigerant into the cycle. Overcharge can lead to excessive system head pressures, which can reduce capacity but also increases compressor power input and reduces compressor life.

In general, smaller A/C units appear to have a higher incidence of low charge because they often receive insufficient maintenance to operate effectively and efficiently (see, for example, Goody et al. 2003). This enables refrigerant leaks to persist for extended periods during which charge levels deteriorate. Larger equipment, notably chillers, often have refrigerant accumulators that buffer the cycle from a certain degree of refrigerant loss. Modern chillers generally also have built-in diagnostic systems which can determine when charge is low.

8.14.2 Fault Energy Impact

Improper levels of refrigerant charge in VC cycles with capillary tube expansion devices can degrade their cooling capacity and efficiency (EER and SEER). Undercharge has a greater impact on SEER than EER (Farzad and O'Neal 1993), presumably due to poorer cycling efficiencies. Undercharge is more common than overcharge;

When refrigerant inventory is low, the evaporator's two-phase heat transfer region is reduced, leading to reduced evaporating pressure and high exit superheat. These conditions result in high compressor discharge temperature and reduced capacity. The reduced inventory in the condenser allows for better approach of condensing temperature to ambient (lower condensing pressure) but negligible subcooling. This causes reduced flow of refrigerant through capillary expansion devices. Low refrigerant charge reduces the amount of refrigerant flowing to the evaporator. The discharge and suction pressures of the compressor decrease, while the compressor outlet temperature increases. The system operates at a higher pressure ratio and lower cycle efficiency. Low refrigerant charge also causes the VC cycle to cycle less efficiently, as lower charge increases the time that the VC cycle takes to reach a steady state (Farzad and O'Neal 1993). Undercharge has a highly non-linear efficiency impact, i.e., a 5% decrease in refrigerant charge has little energy impact, whereas a 15% charge deficit decreases efficiency by around 10% (Farzad and O'Neal 1993, Modera and Proctor 2002).

Overcharged VC cycles actually cycle more efficiently than properly charged units, as the additional refrigerant decreases the time to attain steady state. They too, however, suffer from decreased cooling capacity and efficiency, due to the increased condensing pressure. Overcharged systems with capillary expansion devices also run the risk of liquid return to the compressor. A recent field study suggests that overcharged units are much less common than undercharged units (Rossi 2004).

Vapor compression cycles with thermostatic expansion valves (TXVs) can mitigate the capacity and energy impacts of improper refrigerant charge. The valve actively meters the amount of refrigerant passing through the expansion valve to maintain a preset refrigerant superheat leaving the evaporator. Only a small fraction of VC cycles, however, use TXV units. For example, a study of more than 350 light commercial A/C units in California revealed that 92% of units had fixed orifice expansion devices (Modera and Proctor 2002). Refrigerant receivers can also mitigate improper charging by accumulating overcharge (to a point) and supplying additional refrigerant in the case of low charge. Many chillers and commercial refrigeration systems have refrigerant receivers.

Based on the available data (see Appendix E), between 40% and 80% of RTUs have improper charge (Hewett et al. 1992, Carl and Smilie 1992, Hoover, 2001, Davis et al., 2002, Downey and Proctor 2002, Modera and Proctor 2002, Jacobs et al. 2003, Goody et al. 2003). Furthermore, several sources suggest that the average fault degrades unit efficiency by between 5% and 15% (Farzad and O'Neal, 1993, Breuker and Braun 1998, Goswami et al. 2001, Davis et al. 2002, Modera and Proctor 2002, Jacobs et al. 2003). Nationally, improper refrigerant charge increases RTU energy consumption by between 0.02 and 0.12 quads.

8.14.3 Quality of Existing Data

The existing data focuses almost exclusively on rooftop units and residential split systems. Very little information exists for commercial refrigeration system charge levels; almost none for chillers.

Table 8-29: Data Gaps and Possible Solutions – Improper Refrigerant Charge

Data Issue	Potential Solution(s)
Broad range of fault impact-frequency distribution data	Additional field evaluations, particularly outside of California
Very little data for commercial refrigeration systems, none for chillers	Limited field studies to assess if low or high charge is a problem with these better-maintained equipment types

8.15 General Data Gaps

The energy savings ranges reported in Table 8-30 clearly show the high degree of uncertainty of the potential energy impact of building faults. Controls-related faults for central HVAC systems, in particular, have very large uncertainties. In no case could the data support a CBECS-type analysis of fault energy consumption that segments fault energy impact based on building type and geographic region.

Table 8-30: Estimated AEC Impact Ranges of Faults Selected for Evaluation

Fault	AEC [quads]
HVAC Left on When Space Unoccupied	0.07 – 0.4
Lights Left on When Space Unoccupied	0.02 – 0.36
Duct Leakage	0.17 – 0.38
Dampers not Working Properly	0.02 – 0.1
Airflow Not Balanced	0.02 – 0.16
Insufficient Evaporator Airflow	0.009 – 0.08
Software Programming Errors	0.001 – 0.03
Improper Controls Hardware Installation	0.01 – 0.025
Improper Controls Setup / Commissioning	0.003 – 0.06
Control Component Failure or Degradation	0.023
Valve Leakage	0.0004 – 0.02
Air-Cooled Condenser Fouling	0.005 – 0.012
Improper Refrigerant Charge	0.02 – 0.12
TOTAL	0.34 – 1.8

Nonetheless, this study does provide useful information in several ways about the energy impact of building faults. First, it provides an estimate for the overall magnitude of building faults, i.e., 0.34 to 1.8 quads. Second, it identifies the faults that likely have the greatest national energy impact. Third, it clarifies the specific type(s) of faults have the largest impact within each broader fault type, including primary root causes for specific faults in several cases. Fourth, it points out the data required to improve the fault energy impact estimates for each fault. When combined with the national fault energy impact estimates, this information enables prioritization of future data gathering to focus on faults where the data will prove most useful.

Each fault has particular data gap issues (as noted in the fault-specific subsections, which outline the data gaps and potential ways to address the data gaps). Furthermore, several general issues arose often with the data sources, many of which came from the building commissioning literature (see Table 8-31).

Table 8-31: Common Fault Energy Impact Data Issues

Issue	Effect	Comment
Inconsistent Reporting of Faults between Studies	Complicates aggregation of data from multiple studies, notably for prevalence	Depth and focus of commissioning studies can vary greatly from case to case
Focus on Problem Buildings	Tends to increase prevalence and impact of problems	Several commissioning studies targeted buildings identified as having high energy consumption or comfort issues
Data Format / Detail	Reduces usable data, prevents aggregation of fault-specific results	Many sources did not isolate the energy or cost impact of certain faults or presented values for an aggregate of faults (e.g., entire building)
Geographical Bias	Unclear how prevalence extrapolates to nation	Very large portion of studies performed in California, Texas, and (to a lesser extent) the Pacific Northwest and Florida

The data to address many of these gaps likely exist, but not in the public literature. Energy Service Companies (ESCOs) collect a wide range of proprietary information about the buildings they service to understand the cost-benefit relationship of different energy saving measures, including maintenance and commissioning. Utilities also may have collected similar, proprietary information in support of demand-side management (DSM) programs or their own ESCO activities.

A national study of faults in a set of buildings that adequately represents the national building stock could provide similar information, albeit it at great expense. A more modest approach would be to improve and standardize the quality of fault-related data collected from commissioning studies. This would increase the ability to improve the accuracy of both fault frequency and impact. General ways to improve the uncertainty estimates include the following:

- *Standardize Basic Data Collection for Commissioning Studies* – This would establish a basic list of key energy-related faults to be assessed and reported in commissioning studies, including clear definitions of what faults fall under what categories. In addition, it would establish a similar, minimum standard of precision for characterizing faults in commissioning studies, including the quantity and energy impact of key faults and adequate description/quantification of building systems (building context).
- *Develop a Standard Framework for Cost-Benefit Calculations* – This process would help commissioning agents to break out the energy impact of specific faults instead of lumping together the cost-benefit of multiple measures together. It would also bring greater transparency to fault impact assessments.

Such measures would increase the cost of building commissioning, but interested parties could subsidize commissioning organizations to obtain the needed data. For example, the commissioning protocol developed by the California Commissioning Collaborative[91] could be augmented to include more specific information about key faults and the relevant building systems. It is not clear, however, that this information would substantially alter diagnostic development priorities.

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[91] Information about the California Commissioning Collaborative can be found at: http://www.cacx.org , and their retrocommissioning protocol at: http://www.cacx.org/documents/CRX_PROTOCOL_EXISTING_BUILD.DOC .

9 Assessment of Controls and Diagnostics Approaches

Section 9 presents the analyses of ten controls and diagnostics approaches selected for evaluation, with each sub-section containing the assessment of a single approach. Table 9-1 summarizes the technical energy savings potential of each approach[92], that is, the quantity of energy that the approach could save per year if applied to all of the building stock that could benefit from the approach. The Table also characterizes each approach by its maturity stage (see Table 9-2).

Table 9-1: Controls and Diagnostics Approaches Evaluated

Approach		Technology Status	Relevant Energy Consumption [quad]	Technical Energy Saving Potential [quad]
Diagnostics	Commissioning	Current / New	9.2	0.5 – 1.8#
	Damper Automated Fault Detection and Diagnostics (AFDD)	Current / New	0.85	0.02 – 0.1
	Duct Leakage FDD	Advanced	3.1	0.15 – 0.4
	Packaged Rooftop Unit AFDD	Advanced	0.74	0.024 – 0.14
	Whole Building Energy AFDD	Current / Advanced	9.2	0.5 – 1.8*
Controls	Demand Controlled Ventilation (DCV)	Current	2.7	0.3
	Occupancy Sensor-Based Lighting Control	Current	4.2	0.6 – 2.3**
	Optimal Whole Building Control	Current / Advanced	9.2	0.5 – 1.3***
	Photosensor-Based Lighting Control	Current	4.2	0.4 – 0.8
Enabling	HVAC Sensors	Current / Advanced	4.5	N/A

\# Regular or ongoing ommissioning may save most fault-related energy consumption, except possibly duct leakage.
*Saving from "Commissioning" represents an upper bound for both ends of the range.
**Could also eliminate unintentional "Lights Left on When Space Unoccupied," saving 0.02 to 0.13 quads.
***Includes energy saved from elimination of unintentional "Lights and HVAC Left On When Unoccupied."

Table 9-2: Description of Technology Technical Maturity Stages

Technical Maturity Stage	Description
Current	Technology currently available, but not in broad market areas
New	Technology commercially available, but presently not in use for relevant building systems
Advanced	Technology not yet commercialized or demonstrated, and requires research and development

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[92] The Relevant Energy Consumption and Technical Energy Saving Potential values presented represent more refined values than the preliminary values developed by TIAX in 2003 that are reported in the "The Market for Building Controls - Preliminary Assessment" section of Brambley et al. (2005). Similarly, the assumptions used to estimate many of these values have been updated since the preliminary effort. In all cases, the current values supersede those from the Market section of Brambley et al. (2005).

It is important to note that the energy savings potentials of different approaches are not necessarily additive, as savings realized by one approach can, to varying degrees, decrease and/or preclude energy savings achievable by other technologies. In addition, diagnostics do not, per se, save energy but provide the opportunity to save energy by addressing subpar equipment or system performance. Often, building operators lack the resources (time, personnel or funds) needed to confirm the problem and then fix it (Friedman and Piette 2001; Architectural Energy 2003).

Other approaches not explicitly discussed in this report may also have significant energy savings approach. For example, variable-speed drives (VSD) and energy management and control systems (EMCS) both appear to have the potential for significant national energy savings. The project team decided not to evaluate either option because they both have made significant inroads in commercial building markets, received extensive evaluation in prior research, and technology trends appear to be decreasing the installed cost of both options. Nonetheless, advanced control algorithms that leverage the capabilities afforded by VSD and/or EMCS can achieve significant system-level energy savings if the relevant systems are designed to allow full exploitation of their capabilities (e.g., per Hartman 2005a).

Each write-up follows the same basic format:

- Summary Table (key findings in less than a page);
- Background (what the option is, how it functions in buildings, how it saves energy, commercialization status);
- Performance Benefits (non-energy benefits of approach);
- Energy Savings Potential;
- Cost (economic assessment of approach);
- Barriers (to commercialization);
- Technology Development "Next Steps" (to commercialize or increase market share), and
- References.

Each technology option summary includes the "Relevant Primary Energy Consumption", which equals the amount of energy consumed by commercial buildings systems that the technology option could reduce. Table 8-2 presents the breakdowns of commercial building energy consumption used in this study.

In many instances, the project team estimated the simple payback period (SPP) to quantify the economics of a technology. SPP equals the cost of the energy savings afforded by the technology, C_{Esave}, divided by the incremental premium of the energy efficiency measure, which is the difference between the cost of the default technology, C_{def}, and that of the technology option, C_{opt},:

$$SPP = \frac{C_{def} - C_{opt}}{C_{Esave}}.$$

Unless stated otherwise, all calculations assumed that electricity in the commercial buildings sector costs $0.08/kWh and that gas costs $6.00/MMBtu (see Appendix B). De Canio (1994, from Hawken et al., 1999) found that about 80% of American firms that use some other method than first cost to study energy efficiency investments employed SPP, and that the median threshold SPP was 1.9 years. Hawken et al. (1999) note that this corresponds to a 71% real after-tax rate return on investment (ROI), far in excess of the standard 25% hurdle ROI set for many corporate internal investments.

9.1 Commissioning

9.1.1 Summary

Commissioning is a process designed to ensure that building systems, notably HVAC and lighting, operate efficiently. The process can be characterized by high levels of communication among stakeholders, extensive documentation, thorough testing and checking of building equipment, remedying identified faults and problems, and proper training for operations and maintenance staff to guard against future equipment degradation or failures. The potential energy savings vary from building to building, but commissioning existing buildings can typically reduce their energy consumption by between 5% and 20%, with a payback period of about two years for larger buildings. To date, however, commissioning has a small market share, i.e., less than 5% of new buildings and well under 1% of existing buildings are commissioned in a given year. Automation could expedite commissioning, which would reduce the time, labor, and cost of commissioning, particularly for smaller (<100,000ft^2) buildings, and address concerns about the impact of commissioning on building construction schedules. In addition, building owner outreach programs to increase awareness and understanding of building commissioning could increase its market share.

Table 9-3: Summary of Commissioning

Characteristic	Result	Comments
Technology Status	Current / New	Automated commissioning largely New
Systems Impacted by Technology	All HVAC and Lighting energy consumption; larger refrigeration systems	
Applicable to Existing Buildings and Systems	Yes	
Relevant Primary Energy Consumption [quads]	9.2	All HVAC and Lighting energy consumption; larger refrigeration systems
National Technical Energy Savings Potential [quads]	0.5 – 1.8	Energy savings usually greater for existing buildings than new buildings. Persistence of energy savings is a concern
Non-Energy Benefits	Occupant comfort. Knowledge base for future maintenance	
Approximate Simple Payback Period [years]	1-5 years	Primarily for larger buildings (usually >100,000ft^2); capital cost savings can reduce payback for new buildings

Characteristic	Result	Comments
Key Economic Barriers	Labor costs	
Key Non-Economic Barriers	Time intensive, difficult to schedule (impact on construction schedule), lack of awareness	
Key Enabling Technologies	Automation, wireless sensors, EMCS	Automation will reduce labor costs; sensors with low installed cost may drive installation of more sensors, facilitating commissioning; EMCS facilitates commissioning
Notable Developers of Technology	Facility Dynamics, PECI, Texas A&M, PNNL	
Peak Demand Reduction?	Yes	Effective operation of HVAC systems; HVAC accounts for almost 50% of commercial sector peak demand
Most Promising Applications	Larger buildings with complex HVAC and lighting systems with an EMCS	
Technology "Next Steps"	• Automation of Building Commissioning • Market Promotion of the Benefits of Commissioning • Training of Commissioning Authorities	

9.1.2 Background

The buildings literature suggests that ill-functioning building systems and equipment waste a significant quantity of energy. Most buildings maintain basic levels of functionality, but many suffer from a departure from intended performance due to a wide range of "faults," i.e., deviations from intended or as-designed building equipment and systems performance. These faults compromise the operational efficiency of equipment and systems due to improper installation, insufficient maintenance, or a lack of attention to operations. In addition to increasing building energy consumption, faults may degrade climate control and occupant comfort. The actual energy wasted by different buildings varies greatly and depends on the types of systems in a building, how well building operators maintain the building, and what failures occur. Some building faults do not have a significant effect on building energy consumption, either because they do not have a large impact on building system energy consumption or they are rapidly detected. For example, a fault that often results in decreased occupant comfort will generate complaint calls that cause the fault to be addressed, which limits its integrated energy impact. In some instances, faults can decrease energy consumption, such as an outdoor air damper seized shut. Section 8 discusses analyzes building faults, particularly key faults, in greater detail.

Building commissioning performed in existing buildings or as a step in the building construction process can identify subpar building construction or operation. Specifically, commissioning ensures that building systems, in particular HVAC systems, are designed, installed, and capable of being operated and maintained to perform in conformity with the design intent (ASHRAE 1996). ASHRAE guideline 1-1996 provides a formal definition for the commissioning procedure, with set definitions and phases; plans exist to update this document in the future. In addition, the International Energy Agency (IEA) Annex 40 (Akashi 2003), Portland Energy Conservation Inc. (Haasl and Sharp 1999), and other organizations have also published similar, formal descriptions of commissioning.

An overarching theme is the need to document everything from goals and objectives to data and results for the benefit of the building owner, i.e., to realize well-functioning building systems. Commissioning procedures require people or groups dedicated to overseeing the installation of building systems, known as the commissioning authority (CA). Buy-in and participation of the building owner, CA, design professionals, and construction manager are crucial to realizing an effective building commissioning project. Besides overseeing system design (for new buildings) and installation, CAs also may generate building system design or efficiency investment recommendations, validate and modify system performance, and train building personnel to effectively operate and maintain building systems. Finally, commissioning authorities may periodically check building systems after initial commissioning to ensure proper operation and maintenance.

Commissioning takes different forms depending on whether the building has already been built and whether the building has been previously commissioned. Based on these factors, four types of commissioning exist:

- *Retro-Commissioning*: Retro-commissioning denotes commissioning of existing buildings that were not initially commissioned. This process usually includes developing recommendations to upgrade building systems and improve their function (e.g., modifying building controls such that building systems operate as intended).
- *Recommissioning*: Recommissioning refers to commissioning a building that had been previously commissioned. It may occur multiple times, e.g., every 3 to 5 years, depending on the complexity of building systems.
- *Commissioning New Buildings*: Beginning with the design phase and continuing (at least) through hand over of a new building to its owner, the CA ensures that expectations for the building systems' performance are laid out, documented, and verified.
- *Ongoing Commissioning*: Also known as *continuous commissioning*^{SM}, it involves ongoing optimization of building system operations and control to minimize building energy use based on current, up-to-date building conditions and usage. This process recognizes that building operating objectives and requirements evolve, so the original building system design does not remain optimal forever (Claridge et al. 2003).

The following subsections describe the four basic types of commissioning in more detail. All share the same basic characteristics, i.e., documentation, training, strong communication between stakeholders, and having an unbiased third-party (commissioning authority) perform commissioning. In practice, most actual commissioning projects do not fully incorporate all of the steps described due to budget and time limitations (Mills et al. 2004).

9.1.2.1 Retrocommissioning / Recommissioning Existing Buildings

Retrocommissioning or recommissioning of existing buildings has a greater potential benefit than commissioning new buildings because the building equipment performance has had time to degrade. In addition the original design intent may not be the most energy efficient use of the HVAC system as building use evolved, e.g. occupancy levels and schedules changed. In retrocommissioning, the CA methodically identifies and documents the building owner's objectives and goals. The CA also develops and implements the commissioning plan to evaluate the performance of building systems and develop recommendations to improve their performance. At the end of the retrocommissioning process, the CA verifies that a building meets operational expectations, provides updated building documentation to the building operators, and ensures that building personnel are trained to effectively operate and maintain the building.

Haasl and Sharp (1999) divide retro-commissioning (and the very similar recommissioning) into four phases:

1. *Planning Phase*: Choose commissioning authority; develop objectives; review and update building documentation and historical utility data (past energy usage); develop retrocommissioning plan or review previous commissioning plan (for recommissioning only).
2. *Investigation Phase*: Assess site; list all deficiencies or necessary repairs and potential improvements; develop short-term diagnostic monitoring plans; perform testing, diagnostics, and trending analyses; choose cost-effective improvements.
3. *Implementation Phase*: Implement improvements; retest, monitor, and verify.
4. *Project Hand-off and Integration Phase*: Issue final report; develop recommissioning plan, training, and performance tracking.

The investigation and implementation phases comprise the primary technological and time-consuming phases of the retro-commissioning process. They focus on identifying and remedying deficiencies in building system. A commissioning project would include significant functional testing for energy-consuming equipment. During functional tests, the commissioning agent puts selected systems through a series of operational procedures and compares system behavior to the intended behavior to evaluate system performance. The commissioning agent uses the information from the test to detect deviations from expected performance, i.e., faults, and then diagnose the fault's cause. Relative to passive monitoring of building systems, functional tests can uncover problems that would otherwise take long periods of time to become apparent due to the absence of the conditions needed to reveal the fault.

An example of a functional test of a centrifugal chiller (Haasl and Sharp 1999) illustrates how the CA might identify problems or suboptimal operation of this piece of HVAC equipment during the investigation phase. Before beginning the functional test, the CA verifies that all water pumps and cooling towers operate properly. If an energy management control system (EMCS) is connected to the centrifugal chiller, the CA must also ensure that the chiller's sensors are properly calibrated and located. In lieu of several manual tests, the functional test plan can use data loggers and/or EMCS trend logging to evaluate chiller performance. As described in Table 9-4, the commissioning process examines several aspects of the centrifugal chiller. The test plan is very detailed and labor-intensive.

Table 9-4: Sample Functional Test of Centrifugal Chiller (based on Haasl and Sharp 1999)

Functional Test Sections	Description
Electrical Characteristics	Check for voltage imbalance
General mechanical operation	Measure condenser water flow, chilled water flow, interlocks to pumps, dynamic limits and timers on starter, oil heater safety, etc.
Control Panel	Compare values displayed on control panel to actual measured values. Check that refrigerant leakage alarm and room ventilation are adequate
Full-Load and Part-Load Operation	Measure capacity and efficiency over entire range and compare to manufacturer's data
Chilled Water Temperature Reset Strategy	Use monitoring or data logging to verify intended operation of chilled water reset strategy
Staff Training	Verify proper training of staff responsible for operation and maintenance
Operations and Maintenance Plan	Verify that acceptable O&M plan exists or develop plan

PECI (2003) and Liu et al. (2002) describe functional tests for several other building faults. For example, Liu et al. (2002) presents the following procedure to determine whether or not the ventilation system provides sufficient outdoor airflow:

1. Set room temperature setpoint at 55°F (all terminal boxes should be full open)
2. Disable the economizer
3. Run supply air fan at 25%, 50%, 75%, and 100% and measure:
    a. OA temperature
    b. Mixed air temperature
    c. Return air temperature
    d. Airflow
    e. Duct static pressure
4. Turn off return air fan and repeat Step 3.

The temperature measurements are used to calculate the OA fraction at the different fan speeds, within the error of the different measurements (Liu et al. 2003). If the calculated OA level exceeds the required levels by a certain amount[93], this indicates that the system provides excessive OA. Similarly, if the calculated OA level falls below the required levels by a certain amount, the tool determines that the system provides insufficient OA.

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[93] Presumably, the thresholds take into account measurement accuracies and may also reflect an additional amount of deviation such that the tool diagnoses only more significant faults.

After completing the functional tests, the CA would develop recommended actions to address problems identified. The actual actions implemented depend on their cost-effectiveness and the budget allocated for commissioning activities. In many instances, the owner only implements a portion of actions, e.g., the CA leading a retro-commissioning effort of a five-year old federal courthouse drew up a list of potential improvements or fixes, but the building owner only selected a subset of those recommendations to implement (Baxter et al. 2004). Fixing control problems tends to have attractive economics because they usually require little time to fix and minimal hardware investment (Haasl et al. 2001b). Baxter et al. (2004) also notes that ensuring that operations and maintenance staff members know of changes made during the retro-commissioning process is a cost-effective measure.

In general, commissioning is a very labor-intensive procedure, which keeps its cost relatively high. Several developers have explored ways to automate commissioning to reduce its cost. An evaluation of building commissioning automation identified several parts of the commissioning process that could be automated, including (PECI 2003):

- *Developing and Managing Building Design Information* – Often, the CA collects stakeholder information for the project team, particularly during the design phase;
- *Developing Test Procedures / Commissioning Plans*: Includes identifying test requirements for equipment;
- *Data Management*: Design-related information, i.e., design intent, design concepts, design reviews and changes, etc.; document and track construction submittal comments; O&M documents; functional testing data and results;
- *Performing Functional Testing*: Includes “Automated Whole Building Diagnostics” (see Section 9.10).

Developers have already produced several different software packages to automate each of these tasks; no single package, however, performs all of these tasks. PECI (2003) describes several of these automated commissioning tools in detail.

9.1.2.2 Commissioning New Buildings

Twenty or thirty years ago, the installation of new building systems used to include commissioning. As pressures to reduce costs increased and building systems became more complex, commissioning became a separate, optional service despite the trend toward more complex systems that have a greater need for commissioning (Nolfo 1997).

The commissioning process for new buildings consists of phases that correspond to the state of the building, i.e., predesign, construction, acceptance by owner from contractor (see Table 9-5). Thus, commissioning of new buildings is similar to retrocommissioning but also includes design and construction phases. The phase descriptions reflect the content of ASHRAE Guide 1-1996 and recent modifications to the commissioning process by the IEA (from Akashi 2003). The ASHRAE Guide elaborates further on all phases of the process.

Table 9-5: Phases of Commissioning New Buildings

Phase	Steps	Notes
Pre-design	• Select commissioning authority • Owner lists building objectives • CA develops commissioning plan • CA and owner select building designer	• Corresponds to Planning phase in retrocommissioning • Primarily an information gathering period • Should begin as close to project inception as possible
Design	• CA reviews design intent versus building owner objectives • Prepare schematic design documents • Further develop commissioning plan based on input from designer	• No corresponding phase in retrocommissioning • Modifications will occur to design documents throughout commissioning process
Elaboration	• Bidding, contracts, and arrangement or construction documents	• No corresponding phase in retrocommissioning • New phase not included in ASHRAE Guide1-1996
Construction	• HVAC system installed, started, and put into operation • Review submittals • Finalize commissioning plan • CA audits construction	• Corresponds to Investigation phase in retrocommissioning
Acceptance	• Execute functional tests and diagnostics • Fix deficiencies • Retest and monitor systems • Conduct O&M training • Complete as-built records and system manual • Turn over building to owner	• Corresponds to Implementation phase in retrocommissioning
Post-Acceptance	• Final report from CA to building owner • Continued adjustment and optimization of building systems, in particular perform tests that were deferred • Develop recommissioning plan and schedule	• Corresponds to hand-off and integration phase of retrocommissioning

9.1.2.3 Ongoing Commissioning

Recognizing that commissioning needs to occur continuously or at least on a regular basis, Texas A&M University developed the "Continuous Commissioning^{SM}" (CC) process that emphasizes that the commissioning objectives should evolve as new technologies and uses of the building emerge (Claridge et al. 2003). This document uses the term *ongoing commissioning* to describe both the work of Claridge et al. (2003) and other related ongoing commissioning procedures.

Ongoing commissioning seeks to optimize the operation and control of building systems to minimize building energy consumption and maximize comfort based on current (not initial) building conditions and requirements. In this way, ongoing commissioning places a greater emphasis on persistence, i.e., maintaining energy savings, than retro-commissioning or recommissioning. It consists of the following steps (Claridge et al. 2003):

1. Develop the ongoing commissioning plan and form the project team; similar to planning phase.
2. Develop performance baselines; corresponds to planning or investigation phase.
3. Conduct system measurements and develop continuous commissioning measures; corresponds to investigation phase.
4. Implement continuous commissioning measures; also corresponds to investigation phase.
5. Document comfort improvements and energy savings; corresponds to implementation phase.
6. Keep the commissioning continuous; CA should write a follow-up report to document first-year savings and recommendations; corresponds to project hand-off and integration phase.

9.1.3 Performance Benefits

Commissioning provides many performance benefits for the building owner, the contractor, and the building maintenance staff. Most of these benefits are simply the result of building equipment working properly; other benefits derive from thorough commissioning documentation. The commissioning process also encourages strong communication between the owner, builder/tradesmen, and maintenance staff, which generates additional performance benefits. Table 9-6 lists commissioning results and their corresponding performance benefits based on several sources (Mills et al. 2004, Claridge et al. 2003, Haasl & Sharp 1999, ASHRAE 1996, PECI 1997a). Although non-energy benefits are difficult to quantify, data from a meta study of commissioning suggest that building operators *perceive* the non-energy value of commissioning existing buildings to be, on average, about 2/3rds that from energy savings. For new buildings, analysis of a limited subset of cases that reported non-energy benefits suggests that the non-energy savings exceed the energy savings by roughly an order of magnitude (Mills et al. 2004).

Table 9-6: Non-Energy Benefits of Commissioning

Direct Results of Commissioning	Tangible Benefits of Commissioning
Identify Problems in Building Systems	• Early identification of problems mitigates excessive wear and possible failure • Reduced number of deficiencies at completion reduces call-backs to tradesmen (usually difficult to recall installers after building handover) and change orders
Proper Building System Operation	• Increased occupant comfort (IAQ, temperatures) can enhance productivity and tenant retention; high tenant turnover incurs costs in lease commissions and building renovations • Helps to avoid IAQ problems that increase legal liability of owner/operator
Complete and Accurate Building Documentation	• Documentation provides more information to O&M personnel to improve future diagnoses. • Improved knowledge base for future designs and installations
Appropriate Training for Operating and Maintenance (O&M) Staff	• Documentation provides more information to O&M staff (see above) • Commissioning also provides training to O&M staff that increases their effectiveness, particularly serving occupant needs • Reduces number of calls for operational guidance
Regular Communication Between Owner, Builder, and Building Operators	• Fosters less interference between various trades during design and construction phases • Helps owner meet his expectations for the building

Equipment life, thermal comfort, and indoor air quality (IAQ) ranked as the three most common non-energy benefits in retrocommissioning projects, while reduced change order and warranty claims, decreased first costs, and improved productivity and safety are additional common benefits in new building commissioning (Mills et al. 2004). Large corporations with several highly utilized buildings tend to recognize these performance benefits. For example, Claridge (2003) cites the Disney Corporation and other large corporations (Westin Hotels, Boeing, Kaiser Permanente, and Target) that insist on commissioning. He points out that their buildings are highly utilized by occupants who have very high expectations for comfort and technology. For these building owners, the commissioning ensures proper operation of HVAC systems to provide occupant comfort everywhere in the building from the first day of building operation. Because the occupants have very high expectations for the performance of these facilities, supbar building operation or building system failures have an especially high impact on corporate reputation and customer satisfaction.

9.1.4 Energy Savings Potential

The actual energy savings potential from commissioning any given building varies greatly and depends on the types of systems in place, how well the building operators maintain it, and what failures occur. A significant volume of literature suggests that commissioning typically reduces annual energy consumption by 5% to 20%, with higher values (up to 30%) in some buildings (Mills et al. 2004, Thorne and Nadel 2003, Ardehali and Smith 2002, Parks and Kellow 2000, Claridge et al. 1994, 1996, 1998 1999, Gregerson 1997). A large portion of commissioning work and case studies, however, focus on larger buildings, i.e. those with more than 100,000ft^2. These building are much more likely to have central HVAC systems, particularly ventilation systems that frequently exhibit suboptimal operations (Mills et al. 2004). Assuming that the 5% to 20% range applies to buildings of all sizes, building commissioning has a national energy saving potential of between 0.5 and 1.8 quads.

In practice, however, the energy savings initially gained from commissioning do not always persist because problems arise over time due to equipment aging, changes in usage, alteration in control settings, etc. Consequently, most buildings require follow-up commissioning at regular intervals to maintain higher performance levels. For example, a study of 52 economizers at 22 sites that had been commissioned when built found that 29 had stopped working after "a year or two" (Energy Design Resources 2001). The limited publicly-available quantitative information on commissioning suggests that many buildings and building systems maintain energy savings while others see energy savings degrade by several percent (of savings) a year (Turner et al. 2001; Friedman et al. 2002). Potter et al. (2002) studied ten buildings that were commissioned at least two years prior to their study and found that over half of the commissioning "fixes" persisted. Hardware modifications showed a greater propensity to persist but savings from control strategies often did not persist, presumably due to changes made by operators (e.g., setpoints, scheduling). This shows general consistency with Turner et al. (2001), whose study seems to indicate that many buildings and building systems maintain energy savings while others see energy savings degrade by several percent a year.

9.1.5 Cost

Large variations in energy savings and the cost of commissioning exist between buildings. This reflects differences in building size, system complexity, building maintenance practices and the problems that arise in each building. Data from case studies – which tend to have a greater focus on larger and institutional buildings –suggest that commissioning existing commercial buildings costs[94] between \$0.15 to \$1.00/ft^2, with a median value of between \$0.25 to \$0.35/ft^2 (Mills et al. 2004; Gregerson 1997; Claridge et al. 1999; Haasl et al. 2001a; Hewett et al. 2000; PECI 1997b; Pierson 2001; Energy Design Resources 2001). Data indicate similarly large variations in reported payback periods from one building to another. Average payback periods for retrocommissioning projects appear to be on the order of less than one year (Mills et al. 2004) to to two years (Gregerson 1997, Pierson 2001), without taking into account persistence effects. Due to labor and somewhat fixed costs for meetings and documentation, building commissioning usually has shorter payback periods for larger buildings and buildings with higher energy intensities (energy/ft^2), such as

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[94] Excepting Mills et al. (2004), the data have not been adjusted for inflation. The meta-study of Mills et al. (2004) reports a median cost of \$0.27/ft^2.

laboratories and hospitals (Mills et al. 2004). Similarly, buildings where a few components account for a large portion of total energy consumption tend to facilitate performance monitoring and implementing changes, as does the existence of an EMCS. For example, a 300,000ft^2 hospital (large building with relatively high energy intensity) with large, centralized HVAC systems (large AHUs and chillers) controlled via an EMCS would often be an attractive opportunity for commissioning.

For new buildings, commissioning costs estimates equal approximately 0.6% of building costs (Mills et al. 2004) or 2 to 4% of the initial HVAC system costs[95] (Pierson 2001, CEE 2001, PECI 2002). Estimates indicate that commissioning cost (on a \$/ft^2 basis) ranges from about \$0.35/ft^2 to \$1.15/ft^2 for a large building, depending on building complexity and commissioning scope (several hundred thousand ft^2). A meta-study of building commissioning and a study of the California commissioning market estimated an average commissioning cost of about \$1.00/ft^2 (Mills et al. 2004) and \$1.10/ft^2 (Haasl et al. 2001a), respectively. Typically, the \$/ft^2 cost increases as building size decreases, rising strongly when floorspace falls below 200,000ft^2 and steeply below 100,000ft^2 (PECI 2002; Mills et al. 2004). As buildings with less than 100,000ft^2 account for about 2/3rds of commercial building floorspace (EIA 1999), this suggests that commissioning is currently unattractive for a large portion of commercial buildings based on energy savings alone. Overall, commissioning of larger, new buildings has typical energy-based payback periods on the order of five (Mills et al. 2004) to ten years (Haasl et al. 2001a). The much longer payback periods for commissioning new buildings reflect both lower energy savings and higher costs (Haasl et al. 2001a), presumably due to its integration into the design and building acceptance processes. On the other hand, taking into account non-energy benefits, most notably reductions in capital expenditures (e.g., chiller down-sizing), new building commissioning has an appreciably shorter payback period in many cases, not infrequently providing instantaneous payback (i.e., savings exceed expenditures; Mills et al. 2004).

The commissioning meta-study by Mills et al. (2004) examined the commissioning cost allocations for commissioning existing and new buildings. In commissioning of existing buildings, investigation and planning (69%) and implementation of fixes for faults (27%) combine to account for almost all costs. Limited new building commissioning cost data (for five buildings) indicate that acceptance testing (presumably including adjusting building equipment and systems) accounts for a strong majority of commissioning costs. In all cases, commissioning is labor intensive[96].

9.1.6 Barriers

Commissioning of buildings can identify a wide range of faults and has become a part of the LEED certification process, EnergyStar® buildings program, management of federal buildings, and many utility incentive programs (Mills et al. 2004). New commercial building commissioning rates are, however, less than 5%[97] (Dodds et al. 1998). Retro-

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[95] These values are generally consistent, assuming that mechanical systems account for about 20% of total building cost (McGinn 2005).

[96] Claridge et al. (2003) indicates that ongoing commissioning is also labor intensive.

[97] Public buildings appear to have significantly higher commissioning rates due to mandates and/or practice (RLW 1999; Quantum 2003).

commissioning usually uncovers controls problems in existing building but it is quite rare, i.e., only about 0.03% of existing buildings are commissioned in a given year (Dodds et al. 1998). A review of the commissioning literature suggests that commissioning is particularly rare for smaller buildings, because commissioning costs do not scale linearly with building square footage.

Several barriers, lack of awareness of commissioning, the cost of commissioning, misconceptions about commissioning, schedule concerns, and practical concerns about commissioning, impede greater use of commissioning. A lack of awareness of the existence of commissioning and the up-front cost of commissioning appear to be the primary factors responsible for low commissioning rates (RLW Analytics 1999, Claridge et al. 2003, Thorne and Nadel 2003). Other factors include misconceptions about commissioning, schedule concerns for new building commissioning, and other practical limitations.

Besides a lack of awareness, misconceptions about commissioning hinder its adoption. Many owners believe that retro-commissioning has very long payback periods (Thorne and Nadel 2003). Furthermore, many building owners lack confidence that retro-commissioning can provide the promised benefits, and have misunderstandings of the types of building performance problems that commissioning can address (Thorne and Nadel 2003). For new construction, building owners often assume that systems installation, testing and balancing eliminate the need for independent commissioning or that commissioning is already done (Thorne, Baxter, and Irvine 2001; RLW 1999). Twenty or thirty years ago, the installation of new building systems used to include what is referred to today "commissioning" (Nolfo 1997). The basic system testing carried out today, however, does not incorporate the full range of testing included in commissioning.

Even if building owners are aware of the benefits of commissioning, they typically want to occupy buildings as soon as all building systems *seem* satisfactory so that they can realize a return on their investment (Salsbury and Singhal 2003; Reed et al. 2000). Thus, they do not want commissioning to disrupt the construction schedule (Quantum 2003; PECI 2003)[98]. Other evidence suggests that schedule issues account for a significant portion of *poor* commissioning experiences. In fact, one survey of commissioning EMCS installations in Japan found that adverse schedule impacts accounted for about half of all unsatisfactory commissioning experiences (Yoshida 2003).

In retrocommissioning, operators may resist making changes to existing buildings because they do not want to alter current practices and, thus, risk receiving complaint calls (Claridge et al. 1999).

There are also several practical limits on commissioning (Salsbury and Signhal 2003, Thorne and Nadel 2003). It is difficult to test systems at extreme conditions or for all

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[98] One very small survey of building professionals in New York State found that disruption of construction schedule was usually a less important barrier to commissioning new buildings (Thorne et al. 2001),

conditions. For example, one cannot fully test cooling systems in the middle of winter. Commissioning authorities require very broad knowledge of multiple system and controller types to do testing and interpret results, so few qualified commissioning authorities exist. Building owners have found it difficult to identifying qualified commissioning authorities due to the lack of a widely-recognized certification.

9.1.7 Technology "Next Steps"

"Next steps" for commissioning need to address the largest barriers to greater use of commissioning, i.e., lack of awareness of commissioning and its benefits, the cost of commissioning (particularly smaller buildings), and schedule concerns.

1. *Market Promotion of Commissioning Benefits*: Greater dissemination of the cost and benefits of commissioning to owners can increase their awareness of the benefits of commissioning and address misconceptions about commissioning, e.g., the cost of retrocommissioning. Promotion efforts should focus strongly on non-energy benefits, which often have greater appeal to consumers of commissioning than energy savings. This is particularly true for new buildings, where avoided capital costs appear also to enable greatly shortened or even instantaneous payback. Promotion of commissioning early in the building development process, e.g., incorporating information about into the permitting process for major renovations and new building could help. In addition, a screening tool could help building owners to determine the likelihood that commissioning would prove cost-effective for a given building, for example, based on building energy consumption, floorspace, and building systems. A small but growing portion of new buildings are seeking LEED certification. Currently, LEED for both existing and new buildings requires a "fundamental" level of commissioning and offers points for "additional" commissioning that engages an independent CA, beginning in the design phase (LEED 2002; Arons 2004). If LEED certification continues to grow in importance, notably for existing buildings, it could raise the profile of – and increase owner comfort with – commissioning.
2. *Automation of Building Commissioning*: Automation represents a promising way to reduce labor costs associated with commissioning (see PECI 2003). Commissioning authorities (CA) need to have a thorough understanding of and familiarity with building systems, i.e., high skill levels that typically command higher pay. Automation would help to leverage the CA's skills and reduce her time spend on commissioning a given building to improve the economic of commissioning, particularly for moderately sized buildings. In addition, automated commissioning may help alleviate scheduling difficulties of commissioning by decreasing the time for information gathering, documentation, and some testing[99].

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[99] It is not clear, however, that automation would help to overcome delays that result from fixing hardware problems identified by commissioning. For example, if commissioning identifies a poorly balanced ventilation system, the testing and balancing (T&B) contractor will need to return to the site to redo the T&B. The time required to fix the fault can delay other parts of the construction process.

3. *Training of Commissioning Authorities*: At present, a very limited number of parties offer building commissioning. In at least one part of the country, this appears to limit commissioning activity (Quantum 2003). Nationally, however, it is not clear to what degree this reflects a lack of CAs or market demand for commissioning. An increased number of CAs would increase awareness of commissioning and, via increased competition, drive innovation in commissioning practice, and tend to reduce the cost of commissioning (Thorne and Nadel 2003). On the other hand, commissioning authorities (CA) typically have high skill levels that command higher pay in the marketplace, e.g., from contractors. It is not clear that the building industry can or will provide competitive compensation for these individuals. Certification of CAs by an organization respected by building owners would also increase building owner confidence in hiring CAs (Thorne et al. 2001).

9.1.8 References

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9.2 Damper Fault Detection and Diagnosis

9.2.1 Summary

Outdoor air (OA) economizer damper fault detection and diagnosis can potentially save 0.02 to 0.1 quads nationally by eliminating faults that result in excessive OA intake. Besides saving energy, properly functioning OA dampers ensure proper IAQ and comfort for occupants. Automated fault detection and diagnostics (AFDD) for dampers has been installed and demonstrated in existing air handling units (AHUs), leveraging existing sensors, and could also be readily deployed in packaged rooftop units (RTUs). In particular, factory installation and on-board deployment of damper AFDD in new RTUs and AHUs with microprocessor-based controllers appears to have very favorable economics. On the other hand, the high sensitivity of RTU markets to even small incremental first cost could prevent wide market acceptance. If RTU manufacturers include AFDD with their products, then damper AFDD may become more widespread and realize its energy savings potential.

Table 9-7: Summary of Damper Fault Detection and Diagnosis

Characteristic	Result	Comments
Technology Status	Current/New	Very small market share (PACRAT available; OA/E module a prototype); limited damper faults detected in some high-end RTUs
Systems Impacted by Technology	Ventilation systems with economizers	Outdoor air economizer dampers have greatest energy impact
Readily Retrofit into Existing Buildings and Systems	Yes	AHUs and RTUs often have sensors needed for diagnostics
Relevant Primary Energy Consumption [quads]	0.85	Heating and cooling energy for space served by economizers in 1995. More recently, language incorporated into ASHRAE Standard 90.1 has led to a higher prevalence of economizers in newer RTUs that has likely increased the energy impact of the “dampers not working fault” and, hence, the energy saved by damper AFDD.
National Technical Energy Savings Potential [quads]	0.02 to 0.1	Range reflects the 25-40% prevalence of fault and 10-30% energy impact
Non-Energy Benefits	Preventing damper failures that affect occupant comfort and building IAQ, e.g., insufficient ventilation if outdoor air damper stuck closed	
Approximate Simple Payback Period [years]	Less than one year	For factory-installed systems; much longer for retrofit installations
Key Economic Barriers	• *Retrofit:* Installed cost of sensors and connection to diagnostic program, diagnostics commissioning required for each unit • *New:* Competitiveness of RTU market makes marginal cost increases difficult for manufacturers to accept. • Quantity of existing sensors decreases with smaller capacity RTUs Development of models for normal and faulty damper behavior for different products	
Key Non-Economic Barriers	The need of at least one AFDD approach for additional follow-up evaluation to diagnose faults can dissuade personnel from addressing damper faults; active testing solutions have been identified	
Key Enabling Technologies	Wireless sensors for EMCS-based retrofit installations that require	

Characteristic	Result	Comments
	additional sensors	
Notable Developers of Technology	Facility Dynamics Engineering, Pacific Northwest National Laboratory (University of Colorado developed relevant module),Carrier	
Peak Demand Reduction?	Yes	Faults that increase outdoor air intake can dramatically increase peak cooling loads
Most Promising Applications	Economizers on smaller RTUs (which have a high prevalence of damper failure), located in hot and humid climates	
Technology "Next Steps"	• Market promotion activities to encourage RTU and AHU manufacturers to integrate diagnostics into their product • Incorporate proactive testing into damper AFDD products	

9.2.2 Background

HVAC systems and equipment have several different kinds of dampers that perform different functions, including return air (RA) dampers, mixing dampers, outdoor air (OA) dampers, variable-air-volume (VAV) dampers, and face/bypass dampers. Of these, the OA dampers used in economizers in air handling units (AHUs) and packaged rooftop units (RTUs) have the largest energy impact (see Section 8.5). Dampers control airflows, and when an OA damper fails in an open position, the HVAC system may need to provide more mechanical cooling or heating. In contrast, a damper that fails closed may reduce the OA ventilation rate, causing an IAQ problem. Damper failure can result from a mechanical problem, such as a broken or stuck actuator or linkage that affects the mechanics of positioning the damper. In addition, sensor failures may cause incorrect damper positioning, or the electronic damper control system itself may malfunction. All of these failures can increase HVAC energy consumption.

Because OA damper faults have the largest energy impact, damper AFDD efforts have focused on these units. Notably, two building AFDD computer programs, the Whole Building Diagnostician (PECI 2003) and PACRAT (Facility Dynamics 2004), incorporate damper-related diagnostics. In both cases, damper-related diagnostics represent a relatively small portion of the full capabilities of both programs.

Ventilation systems have two primary functions related to the OA damper: to supply at least the minimum level of OA required by ASHRAE Standard 62 and to reduce air-conditioning energy consumption via economizing, i.e., using cooler OA to cool the building when the OA temperature (or enthalpy) falls below indoor air levels. In response to economizer controller signals and/or occupancy[100], the dampers are adjusted[101] to set the amount of fresh OA brought into the building and the amount of return air exhausted to the outside (see Figure 9-1).

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[100] See Section 9.3, "Demand Controlled Ventilation".

[101] Systems usually provide two-position or full modulation control.

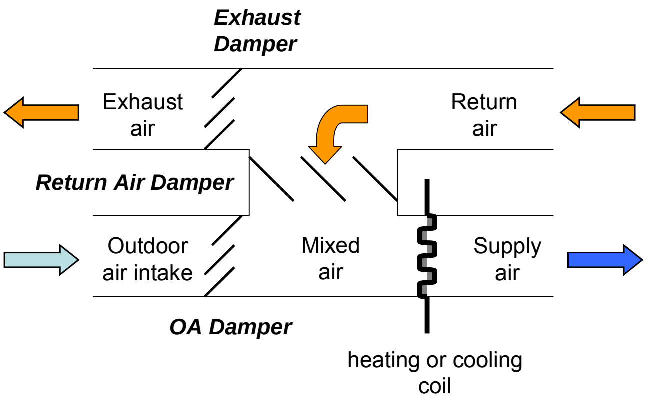

Figure 9-1: AHU Ventilation Schematic

Closing the OA damper causes the RA to recirculate into the building. If the OA damper remains open on a cold winter day, the heating system will have to heat up a large intake of cold air before sending it into the building. This is a significant waste of heating energy. Conversely, if the OA damper is closed when the OA temperature is appreciably cooler than the indoor air temperature at a time when the unit is in cooling mode, the AHU wastes cooling energy by using mechanical cooling to cool down the RA instead of introducing the cooler OA.

Typically, AHU controls maintain a set supply air temperature (or sometimes mixed air temperature; Katipamula et al. 1999). The AHU mixes the RA with the OA and then the blower draws the air through the heating and cooling coils. Typically, electric actuators control the dampers, although some systems continue to employ legacy pneumatic actuators. To determine the appropriate mixture of outdoor and return air to supply to the space, AHUs employ one of several different economizer control strategies to prevent excessive moisture intake and to insure that economizing saves energy (i.e., that the additional fan power required to move the additional OA does not exceed the cooling benefit derived by the economizer; see Section A.2.1 for a description of economizer control strategies). All economizer control strategies rely on temperature and/or humidity sensors to determine the desired OA fraction and, thus, the position of the dampers. As a result, sensors that fail or provide inaccurate readings to the control system may result in inappropriate damper positioning that increase energy consumption.

Damper AFDD schemes can be divided into two classes: passive and proactive (PECI 2003). The passive schemes detect faults by monitoring system performance, while proactive fault detection uses functional testing (i.e., introducing targeted system inputs to check system functionality in response to the functional tests). The biggest advantage of proactive schemes is that some faults may take long periods of time to become apparent due to the absence of the conditions needed to reveal the fault. For example, long periods of hot weather with the OA damper stuck closed will not trigger an alarm. Proactive schemes typically are also more sophisticated and hence costly, so the current AFDD systems are mostly passive.

Three basic approaches exist for damper AFDD: damper position sensing, thermodynamic-based, and flow-based. At least one existing product uses a digital damper motor to determine damper positioning faults, including limited range of motion, stuck dampers, damper actuator failure, and improper damper actuator switch setting (Carrier 2004). It cannot, however, determine if sensors integral to damper control have fallen out of calibration, which is crucial to assessing the appropriateness of a given damper position. Most developmental work to date has focused on the thermodynamic approach, i.e., comparing expected and actual temperatures in the operational context of the damper. Consequently, most of this section will focus on the thermodynamic approach.

Two diagnostic programs, Outdoor Air Economizer (OAE) and PACRAT, use thermodynamic models of the RA and OA flows and process operational measurements (typically acquired from an energy management control system [EMCS]) to detect and diagnose faults. Pacific Northwest National Laboratory began developing the OAE module for their more comprehensive Whole Building Diagnostician tool (see also Section 9.10) in the 1990s. The program is still in the prototype stage and has been updated as recently as 2003 (PECI 2003). The OAE analyzes measurements from sensors commonly installed in AHUs and RTUs (see Table 9-8) using rule-based programming and statistics to detect and diagnose faults in constant-air-volume (CAV) and VAV systems that maintain the OA intake as a constant fraction of the supply air flow. It supports all of economizer control schemes described in Section 4 (PECI 2003) and can detect and help to diagnose several damper-related faults, including (Brambley et al. 1998, Friedman and Piette 2001):

- Lack of economizer cooling;
- Excessive or inadequate OA;
- Unnecessary mechanical cooling (from suboptimal economizer operation), and
- Mis-calibrated, suspect, or failed sensors.

The OAE uses a decision tree to detect – and in some cases, diagnose – damper malfunction and the malfunction of sensors used for damper control (PECI 2003 explains the decision tree in greater detail). The OAE employs a serial detection scheme and stops after detecting a fault or determines that no faults exist. It does not identify multiple simultaneous faults (PECI 2003). At each point of the decision tree, it uses system performance data, i.e., heating and cooling status, and OA, RA, and MA temperatures, and compares the values to each other and expected values to assess economizer operation. The OAE module also performs energy and mass balances based on the data to assess damper performance.

Figure 9-2 presents the decision tree for potential temperature sensor problems. For example, it is not possible for the MA temperature to be lower or higher than both the RA and OA temperatures because the MA consists of a mix of RA and OA. Consequently, the system diagnoses a temperature sensor fault[102] if the MA temperature (plus its measurement uncertainty) is lower or higher than both the measured RA and OA temperatures (given their uncertainties).

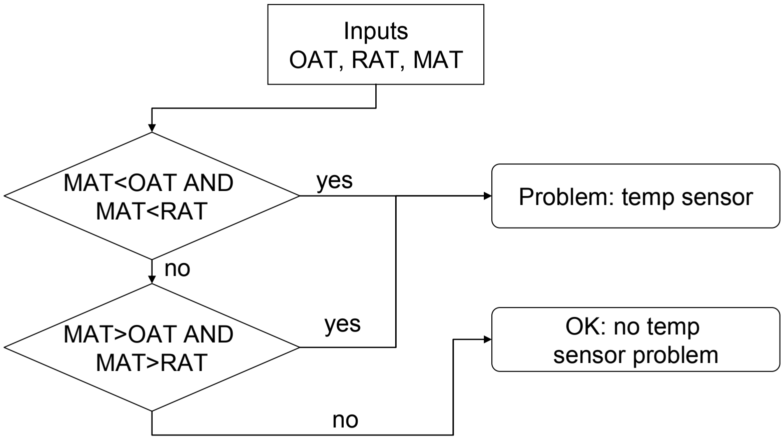

Figure 9-2: Damper Diagnostic Algorithm to Isolate a Temperature Sensor Problem (from PECI 2003)

In contrast, detection of inadequate OA involves both mass and energy balances. First, the AFDD algorithm validates that the temperature sensors provide reasonable measurements. Subsequently, it calculates the estimated OA fraction (OA%) using RA, OA, and MA temperature (and, possibly, enthalpy) measurements via energy, mass, and moisture balances. Next, it considers measurement errors to develop an approximate OA% range[103] and compares the estimated range to minimum OA% setting for AHU. If the estimated OA% lies below the minimum OA% taking into account possible measurement errors, e.g., based on the high-end estimate of OA%, the AFDD determines that an inadequate OA fault exists and may indicate improper damper position.

In some instances, the OAE can only narrow down a detected fault to two or three possible reasons, in which case the OAE still requires manual diagnosis of problems, i.e. the system is not fully automated (Brambley et al. 1998, PECI 2003). For example, in one case the OAE determined that the AHU took in too much OA and diagnoses two possible causes: an OA damper stuck open (damper stuck or linkage broken), or a failed air-temperature sensor (Brambley et al. 1998).

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[102] In this instance, it is not clear what temperature sensor has failed.

[103] For example, OA% ≈ (MAT-RAT)/(OAT-RAT). If measurements show MAT=20°C, RAT=28°C, and OAT=15°C, the estimated OA%=62%. Given a sensor error of ±0.5°C, the OA% could be as high as 69% {=(19.5-28.5)/(15.5-28.5)} or as low as 54%{=(20.5-27.5)/(14.5-27.5)}. Thus, an AFDD algorithm would likely calculate a potential OA% range using this or a similar procedure to avoid false alarms due to sensor error.

To avoid false positives driven by faulty data, the OAE includes a high-low range checking procedure of the measured data (e.g., ensuring that an OA temperature value falls within reasonable range given the time of year). In addition, tolerances are specified for measurements and variables derived from measurements to attempt to eliminate spurious fault detection (Brambley et al. 1998, PECI 2003). Recently, the OAE developers have investigated the potential of using long-term historical data to improve fault detection accuracy (e.g., comparing performance evolution/trends) and adding proactive diagnostics to detect faults before they occur (e.g., via functional testing, see Section 9.1.2; PECI 2003). The OAE developer has attempted– but has yet – to commercialize the more comprehensive AFDD tool that includes the OAE module.

The OAE allows for variable data collection periods, although typically data are recorded every hour. The initial data requirements for OAE (PECI 2003) are:

1. A description of the basic air handling system (economizer type, control strategies, and set points);
2. Minimum, maximum, and design (fully occupied) outdoor air fractions;
3. The operating and occupancy schedule to identify when peak and minimum OA must be supplied, and
4. Data to assess the importance of a fault (e.g., whether to announce a fault or not) based on its estimated energy and cost impact (utility rate structure, energy waste calculations).

PACRAT is a commercially available AFDD software package that incorporates very similar damper-related AFDD capability for AHUs as the OAE (Friedman and Piette 2001, Facility Dynamics 2004). It, too, uses a thermodynamic-based approach and leverages several existing sensors (see Table 9-8). To detect possible OA temperature sensor failures, PACRAT can access NCDC weather data (e.g., via the Internet) and compare reported OA temperatures with building-measured values. This comparison can reveal calibration problems, as well as issues with sensor placement. For example, OA temperature is a key explanatory variable[104] in the models used in damper diagnostics, which makes it crucial to effective diagnostics operation. A poorly placed OA sensor, e.g., exposed to the sun, will tend to read higher temperatures[105], which, in turn, can lead to erroneous diagnoses (false positives and false negatives).

Field testing has validated the ability of thermodynamic-based damper AFDD approaches to detect damper-related faults. Two field tests were carried out to evaluate the OAE's ability to detect faults in three and four AHUs, respectively, using existing sensors. In these tests, a dynamic data exchange (DDE) connection was used to transfer the sensor data to the OAE computer program. The OAE detected sensor malfunctions and return-air dampers not fully

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[104] That is, it has a major influence on energy consumption predictions.

[105] The OAE detected a problem with an OA temperature sensor in one field test, although it could not diagnose that sensor placement caused the problem.

closing, all of which were confirmed manually. In addition, the OAE was tested with building system data sets generated by DOE-2[106] simulations that incorporated several different damper faults. Typically, diagnosis of a fault required additional reasoning by buildings operations and maintenance personnel (Katipamula et al. 1999).

One field test of PACRAT monitored eight AHUs at a pharmaceutical campus in the Midwest for six months. The diagnostics correctly detected 97% of the twenty-five sensor errors that occurred correctly and the single economizer anomaly[107] (Santos and Rutt 2001). Another field evaluation of PACRAT included 34 AHUs at the National Security Agency over a twelve-month period. The reported results did not focus on the damper diagnostic functions of PACRAT in this field study, but did note that the diagnostics prioritized the repair and replacement of the most critical detective damper actuators. In addition, PACRAT validated that the AHUs met ASHRAE Standard 62-1999 ventilation requirements (Santos and Rutt 2001).

An alternative to thermodynamic damper AFDD schemes described above is a flow-based scheme based on fan power and air-side pressure drop over the dampers to evaluate actual damper position (PECI 2003[108]). Essentially, the relationship between fan power draw and damper pressure drop varies with damper position and a comparison of actual supply fan power draw or damper pressure drop to reference values could enable detection of incorrect damper position. This approach has two potential downsides relative to the thermodynamic approaches described earlier, and both will tend to increase its implementation cost. First, it requires a commissioning process to learn the pressure drop and/or power draw as a function of damper position under normal and faulty conditions. Second, it requires additional sensors not normally deployed in AHUs (PECI 2003) or RTUs, i.e., power meters and differential pressure sensors. Consequently, the rest of this section focuses on thermodynamic-based damper AFDD.

9.2.3 Performance Benefits

Damper AFDD addresses several potential indoor air quality (IAQ) and occupant comfort issues that can arise due to OA damper failure. If an OA damper or exhaust damper fails in a closed position, the quantity of OA reaching the building occupants decreases. As a result, IAQ may suffer and the HVAC system may fail to comply with the minimum OA requirements of ASHRAE Standard 62, which could expose the building owner to liability. If the OA damper fails in an open position, this increases the stress on the ventilation, cooling and/or heating systems, which can shorten equipment lifetime. On a hot day, the additional load may prevent the mechanical cooling system from maintaining the desired space temperature and humidity, which can decrease occupant comfort.

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[106] DOE-2 is a computer program to simulate the energy performance of buildings.

[107] The source does not note specific anomaly that occurred.

[108] See section 8.10.2.

9.2.4 Energy Savings Potential

In each AHU or RTU that has economizer dampers that fail in the full-OA position, damper AFDD would save between 10 to 30% (cooling and heating) energy. Elimination of all economizer damper faults would have an annual energy saving potential of between 0.02 and 0.1 quads nationwide (see Section 8.5). This value will likely increase in the future as economizer units become more prevalent, in particular due to language in ASHRAE Standard 90.1 that effectively prescribes economizers for many units. Damper AFDD also reduces peak demand because an open OA damper increases cooling loads and peak electric demand typically coincides with high OA temperatures.

As with all diagnostics approaches, damper AFDD does not save energy unless building operators take action in response to faults. Very limited field testing of the OAE software found that building staff often did not remedy problems identified by the OAE because they were busy, did not want to take the time to isolate faults with multiple potential causes, or lacked the authority to initiate repairs (Architectural Energy 2003).

9.2.5 Cost

Costs are not available for the two thermodynamic approaches discussed at some length, i.e., the OAE module of the WBD and PACRAT, as both are portions of larger diagnostics programs. In general, units with dampers have both static (e.g., occupancy schedule, equipment specifications) and continuously measured data requirements (e.g., temperatures, damper position; PECI 2003). Damper AFDD diagnostics will incur incremental costs for:

- Capability to carry out AFDD logic and calculations;
- Development of the setup information needed for the AFDD tree(s) of each particular AHU/RTU system type, and
- Deployment of additional sensors, including their communications infrastructure.

The diagnostics software (logic) will need to be installed in retrofit applications, either by reprogramming an existing DDC controller, installing a new DDC controller, running the AFDD software on a PC, or as an add-on to an existing EMCS. In general, these options are time-consuming and would require an expensive site visit to implement the AFDD. Similarly, each existing AHU or RTU product may have somewhat different information for its AFDD decision tree. If retrofitted into existing units, damper AFDD will require *in situ* determination and/or communication of the system characteristics (e.g., economizer control scheme, control set points, and damper position control characteristics) to the AFDD software. As noted earlier, thermodynamic-based damper AFDD leverages sensors that exist in many RTUs and AHUs with differential enthalpy-based economizer control[109] (see Table 9-8; sensor OEM cost estimates based on Sections 9.5 and 9.8), but implementation of one or two additional temperature sensors would add more cost.

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[109] #A recent survey of new commercial buildings in California found that enthalpy-based economizer control was the most common type of economizer control for smaller RTUs (Architectural Energy 2003).

Table 9-8: Characteristics of Sensors Used for Economizer Damper Diagnostics

Sensors	Diagnostic Approach		Unit – Usually Has Sensor?		Sensor OEM Cost [$]
	OAE	PACRAT	RTU	AHU	
OA temperature	Yes	Yes	Yes	Yes	
Return air temperature	Yes	Yes	Maybe	Maybe	<5
Mixed air temperature	Yes	Yes	Maybe	Yes	<5
Supply fan on/off	Yes	Yes	Yes	Yes	
Supply fan cfm or %VSD	No	Yes	No	CAV=No VAV=Yes*	
Heating status	Yes	Yes	Yes	Yes	
Cooling status	Yes	Yes	Yes	Yes	
OA relative humidity (RH) / Enthalpy	Yes	Yes	Yes	Yes	
Return air RH / Enthalpy	Yes	No	Yes	Yes	
Supply air temperature	Yes	Yes	No	Yes	<5
Desired OA damper position	Maybe**	Yes	Maybe**	Maybe***	

* % VSD.

**Smaller RTUs likely to have two-position damper control while larger RTUs may have damper position control.

*** Requires damper position signal if AHU uses damper position control to control either OA rate, mixed air temperature, or supply air temperature (PECI 2003).

The infrastructure needed to communicate the sensor signals to the AFDD software has a larger impact on the AFDD system cost than additional sensors. For existing AHUs or RTUs controlled by an EMCS, the EMCS signals would need to be relayed to the PC hosting the damper AFDD software unless the AFDD capability were programmed into the EMCS. The labor required for installation of either option, particularly to extract EMCS data and relay it to a PC, makes them unattractive. For AHUs or RTUs *not* controlled by an EMCS or existing RTUs, the sensor signals need to flow to the PC hosting the damper AFDD software, via either hard wiring in the building or wireless communications. This can be quite expensive, e.g., costs of between $80 and $300 per sensor[110] have been estimated to integrate new hard-wired or wireless sensors (Kintner-Meyer and Brambley 2002, Katipamula and Brambley 2004; see Section 9.5).

On the other hand, factory-installed damper AFDD capability would have much lower implementation costs. In that case, each AHU[111] or RTU's microprocessor-based controller[112] would obtain the relevant unit information and settings, acquires the necessary data, and performs diagnostics assessments locally. The very low data rates and light computational requirements of damper AFDD (e.g., in contrast to RTU AFDD), facilitate on-board implementation.

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[110] For an installation with up to six RTUs, including sensor cost (see Section 9.5.4).

[111] Large built-up AHUs are not factory assembled. They often would tend, however, to have greater sensor capabilities. Furthermore, their size would make reduce incremental cost to add damper AFDD on a *percentage* basis.

[112] Some new AHUs and RTUs have a microprocessor-based controller, particularly larger units (which often have VAV).

If damper AFDD requires one or two additional sensors, factory installation greatly decreases their implementation cost, i.e., installation (not including the cost of the sensor) in an RTU[113] would add a few dollars to the manufacturer's cost, with labor and wiring costs accounting for most of the installation cost (TIAX Manufacturing Cost Estimate). To communicate a fault to building personnel, the on-board AFDD system would leverage the existing communication systems. In the case of an EMCS, the controller would simply relay the presence of a fault to the EMCS. For units not connected to an EMCS, e.g., controlled by a thermostat, the RTU controller would relay the fault to a thermostat with a fault indicator[114]. Building personnel would then consult the unit controller to determine the nature of the fault. Although thermostats with this capability appear to have a small market share, they should have a significantly smaller incremental cost than establishing a full-blown communications link.

Overall, damper AFDD should have an incremental OEM cost of about \$10[115], not including development costs. For a statistically significant[116] number of RTUs, assuming a two-fold markup and that 1/3rd of RTUs have an OA economizer damper fault that increases cooling and heating energy consumption by 20%, damper AFDD should pay back in well under one year[117].

9.2.6 Barriers

The cost of retrofitting damper AFDD into AHUs and RTUs appears to preclude such implementations. Factory integration, on the other hand, looks much more attractive. Although many units have the sensors needed for damper AFDD, it appears that no units incorporate thermodynamic damper diagnostics. Four barriers impede its deployment in new units. First, manufacturers have limited development resources and may be reluctant to invest the time and effort required to develop damper AFDD algorithms tailored to their equipment, particularly if they perceive little demand for diagnostics in general. In particular, focus group research for more comprehensive AFDD software suggests that end users want systems and equipment integral diagnostics, harbor skepticism about energy saving claims, and are wary of time-consuming false alarms (Heinemeier et al. 1999). This supports the premise that damper AFDD should be integral to units (invisible to end users) and have stringent criteria for fault detection to avoid false alarms (see Section 4.2). Similarly, equipment manufacturers, distributors, and installers will likely avoid AFDD that does not have very low false alarm rates because higher rates could substantially increase the cost of servicing and managing their products (to address the false alarms).

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[113] It is not expected that incorporation of additional temperature sensors into an AHU would cost appreciable more.

[114] For example, the Honeywell T8511M.

[115] Assuming roughly \$5 for the microprocessor, less than \$5 for an additonal sensor, and less than \$5 for installation and additional wiring.

[116] Damper AFDD will only provide a benefit for economizers that develop a problem, i.e., only 25% to 40% of economizersare estimated to have a significant OA damper fault.

[117] Additional assumptions: 10-ton RTU serving 4,000ft^2, average commercial floorspace cooling and heating costs of \$0.20ft^2 and \$0.22/ft^2, respectively (based on ADL 2001, \$0.08/kWh, \$6.00/MMBtu for natural gas). This yields energy cost saving of ~\$110 (= 4,000 ft^2 * {\$0.20/ft^2 + \$0.22/ft^2} * 33% * 20%). Peak electric demand charges would increase the economic benefit of energy consumption reductions from damper AFDD.

Including damper AFDD could, however, enable manufacturers to differentiate their products in the market place. Second, even if the incremental cost of incorporating damper AFDD functionality appears to be very low, customers may still not accept even small cost increases, particularly for the highly competitive RTU market. Third, the OAE unit provides multiple possible diagnoses for detected problems, such as temperature or humidity sensor problems. Very limited field testing suggests that the need for further follow-up by building operations personnel decreases the likelihood that the detected problem will be fixed (Architectural Energy 2003). Proactive diagnostic approaches to address this issue exist, e.g., setting dampers at 0% and then 100% OA and comparing measured temperatures (PECI 2003). They can, however, result in undesirable operating conditions unless the tests have sufficiently short durations to provide the data with limited comfort impact. Alternately, the AFDD system could carry out proactive testing during unoccupied periods (if known) to avoid conditions that compromise occupant comfort. To some extent, detailed weather microdata could substitute for active testing designed to isolate sensor faults (as used in PACRAT).

9.2.7 Technology "Next Steps"

Damper AFDD can result in significant energy savings for improperly operating outdoor air economizer dampers. Larger AFDD programs have come to market that incorporate thermodynamic damper AFDD, but they have negligible market share. Similarly, factory-installed damper AFDD appears to have very little incremental cost impact but needs to overcome the lack of customer demand for damper AFDD and mitigate the lost opportunity cost of damper AFDD development costs. Although high-end units might incorporate damper AFDD to differentiate their products, additional development/design support would substantially increase the likelihood that manufacturers would deploy damper AFDD. Larger RTUs and central AHUs would be logical candidates. In sum, overcoming damper AFDD development costs incurred by the manufacturer is the key to its market penetration.

1. *Incorporation of Basic Thermodynamic Damper AFDD into Factory-Produced Commercial Units:* The approach has been retrofitted into units, i.e., the technical concept has been demonstrated, but the aforementioned financial barriers remain to be overcome.
2. *Incorporation of Proactive Damper AFDD into Factory-Produced Commercial Units*: In some cases, thermodynamic damper AFDD models require follow up by buildings personnel to diagnose which of multiple potential faults has occurred, e.g., for some sensor faults (PECI 2003). The time required for building personnel to isolate the actual fault can cause personnel to ignore the fault. Proactive testing can diagnose specific faults and increase its real value to building personnel. This refinement of damper AFDD requires a little more sophistication than basic thermodynamic damper AFDD to implement.

9.2.8 References

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9.3 Demand Controlled Ventilation (DCV)

9.3.1 Summary

Demand Controlled Ventilation (DCV) is a controls approach for all commercial air-conditioning that modulates the amount of outdoor air (OA) intake, usually based on carbon dioxide (CO_2) levels measured in the conditioned space. DCV has the greatest energy saving potential in buildings that have highly variable occupancy levels and that are in more extreme climates. The estimated national technicalenergy savings potential for DCV is at least 0.3 quads based on simulations and limited field test results. In general, DCV systems have a simple payback period of approximately two to five years with the CO_2 sensors, DCV controller, and the installation being the key cost components. The key non-economic barrier to wider DCV implementation is confusion about whether or not DCV satisfies the requirements outlined in ASHRAE standard 62-2001 to attain acceptable indoor air quality for the building occupants.

Table 9-9: Summary of Demand Controlled Ventilation

Characteristic	Result	Comments
Technology Status	Current	DCV appears to have a very limited market share (BCS 2002)
Systems Impacted by Technology	All commercial air-conditioning	
Readily Retrofit into Existing Buildings and Systems	Moderately difficult:	Installation of CO_2 sensors in conditioned space and connection of CO_2 sensors to outdoor air damper controls. Four hours' installation time (Braun 2003).
Relevant Primary Energy Consumption [quads]	2.7 / 1.5	All heating and cooling energy except individual units, VAV ventilation energy[118]; more promising building types[119] account for about half the energy (second number)
National Technical Energy Savings Potential [quads]	0.3 / 0.2	Conservative estimate of 10% of both cooling and heating energy; large variations in practice reflecting building type, actual versus design occupancy level patterns, climate; more promising building types account for about half the energy (second number)
Non-Energy Benefits	Can detect and	Maintaining proper indoor air quality (IAQ) will

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[118] In practice, DCV impacts only the energy used to heat and cool outdoor air, as well as ventilation energy consumption in VAV systems. Data for the percentage of commercial building heating cooling loads attributed to conditioning outdoor air are not readily available. A simple analysis of binned load and weather data found that outdoor air accounted for about 50% and 25% of an office building's annual heating and cooling loads, respectively (TIAX 2002). Mercer and Braun (2005) cite a range of 20% to 40% for both heating and cooling (from the **1993 ASHRAE Handbook**). The energy saving percentage of 10% is calculated relative to *all* heating and cooling energy, as this is the format most commonly used in prior studies.

[119] Mercantile and service, food service, and public buildings (assembly, order and safety, religious worskhip) from ADL (2001).

Characteristic	Result	Comments
	compensate for low outdoor air (OA) rates	increase occupant comfort and health.
Approximate Simple Payback Period [years]	2 to 5 years	Large variations reflecting actual versus design occupancy level patterns, building type, climate, floorspace served
Key Economic Barriers	Cost of CO_2 sensors, retrofit Installation	
Key Non-Economic Barriers	Regulatory barriers and IAQ assurance	Confusion surrounding DCV implementation under ASHRAE Standard 62
Key Enabling Technologies	Less expensive, more reliable sensors for CO_2 and other airborne pollutants	
Notable Developers of Technology	Carrier, Trane, Telaire, Texas Instruments	
Peak Demand Reduction?	Yes	Actual reduction depends on OA contribution to peak demand building occupancy patterns
Most Promising Applications	Buildings and/or spaces with high design occupancy and high variability in actual occupancy, e.g., theatres	
Technology "Next Steps"	• Increase industry comfort in applying DCV by clarifying language in ASHRAE Standard 62 impacting DCV • Reduce cost and increase robustness of CO_2 sensors	

9.3.2 Background

Indoor Air Quality (IAQ) affects the design, construction, and operation of HVAC systems. Minimum outdoor air (OA) rates were reduced in the early 1980s to reduce the energy expended to condition the OA, but they contributed to the onset of sick building syndrome in buildings. Sick Building Syndrome (SBS) refers to buildings with high levels of occupant complaints about comfort as well as perceived and actual health effects caused by poor IAQ. Pollutants from several sources can cause IAQ problems, including: building occupants, construction materials, building operations/equipment (e.g., copiers), and outdoor contaminants introduced via the ventilation system, and microbial growth in ducts. Recently, mold has become a significant concern in the buildings industry (McDonald 2003; ACHRN 2003). In many cases, non-HVAC issues (e.g., roof leaks) create conditions favorable to mold growth, but poor ventilation can exacerbate the condition.

To address this problem, OA rates were increased threefold in ANSI/ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality". Until recently, required OA ventilation rates scaled with the maximum occupancy of buildings and were fixed; in practice, however, most real-time occupancy levels fall short of maximum design levels. Therefore, the buildings have excess OA entering spaces during periods of low to zero occupancy that requires extra energy to heat or cool. Demand Controlled Ventilation (DCV) regulates the amount of OA coming into a building on the basis of varying occupancy levels.

ASHRAE 62 is the widely-accepted standard for providing ventilation to maintain indoor air quality. Both fixed ventilation rate *and* DCV systems adhere to the ventilation rate guidelines in ASHRAE 62. The original 1989 edition was followed by editions in 1999, 2001, and 2004. ASHRAE 62 has two procedures for maintaining IAQ, the Ventilation Rate Procedure and the Indoor Air Quality (IAQ) Procedure.

The Ventilation Rate procedure prescribes OA rates on a cfm/ft^2 basis as function of occupancy and building type. Table 9-10 shows prescribed ventilation rates for some building types, based on Table 6.1 "Minimum Ventilation Rates in Breathing Zone" of Addendum n to ASHRAE 62-2001. Typically, a constant air volume (CAV) system has a minimum position for the OA damper to ensure that it provides the design minimum OA rate, for example, 17[120] cfm per person in an office at design occupancy based on the values shown in Table 9-10). A DCV system always provides spaces with the minimum required OA rate based on floorspace and increases the ventilation rate as occupancy increases, i.e., by the product of the minimum per-person OA rate and occupancy.

Table 9-10: Prescriptive Minimum Ventilation Airflow Rates for Some Building Types (based on ASHRAE 2001)

Building Type	Area-Based OA [cfm/ft^2]	Occupancy-Based OA [cfm/person]	Default Occupant Density [person/1,000 ft^2]	Design Minimum OA [cfm/ft^2]
Office Space	0.06	5	5	0.085[121]
Retail - Sales	0.12	7.5	15	0.233
Public Assembly[122]	0.06	5	150	0.81
Schools[123]	0.12	10	35	0.47

The IAQ Procedure dictates monitoring and restricting the concentration of all known contaminants of concern to acceptable levels, i.e., it relies on subjective identification of contaminants and quantitative evaluation their concentrations. It also provides for recirculation of the indoor air with air-cleaning systems to restrict contaminant levels. Furthermore, design criteria and assumptions about IAQ need to be documented and reevaluated on a periodic basis. Because the IAQ procedure requires control over all known contaminants of concern such as formaldehyde, organic compounds, tobacco smoke, etc. the CO_2 sensor used as a proxy for occupancy in DCV systems is simply not adequate to guarantee adequate IAQ. Interpretation IC 62-2001-17 of ASHRAE Standard 62-2001 confirms this:

> "The Air Quality Procedure requires consideration of many more factors than the level of CO_2. Therefore, CO_2 control of outdoor air intake or the filtration of CO_2 can not be used as sole proof of compliance under the Air Quality Procedure." (ASHRAE 2002a)

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[120] In this example, each person has 200ft^2, so 0.085cfm/ft^2 * 200ft^2/person = 17 cfm/person. For comparison, ASHRAE 90.1-1999 required 15 cfm/person.

[121] For clarity, 0.085 cfm/ft^2 = 0.06 cfm/ft^2 [AREA-based] + 5 cfm/person * 5 persons/1,000ft^2 [OCCUPANCY-based]

[122] The table references the value for Lobbies.

[123] Classrooms (age 9 and above).

This interpretation effectively rules out satisfying ASHRAE 62-2001 with DCV using the IAQ procedure.

On the other hand, using CO_2 as a proxy for occupancy, DCV can satisfy the Ventilation Rate Procedure more easily. The Ventilation Rate Procedure "is deemed to provide acceptable indoor air quality, *ipso facto*;" (ASHRAE 2001) so, the language of the Ventilation Rate Procedure has little ambiguity in providing acceptable IAQ. The latest change to ASHRAE 62-2001 that impacts DCV is addendum n. Addendum n modifies the Ventilation Rate Procedure to include a non-zero ventilation rate at zero occupancy to dilute contaminants produced by the building itself (e.g., furnishings, rugs, office equipment). Prior to the introduction of addendum n, the required ventilation rate equaled zero when the space was unoccupied (see Figure 9-3).

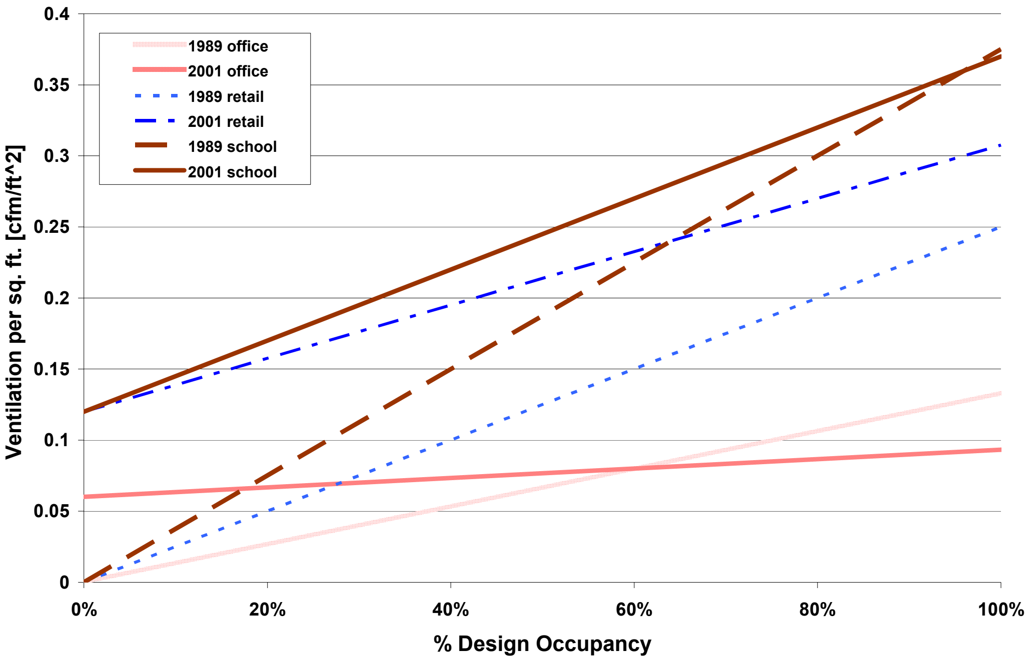

Figure 9-3: of ASHRAE Standard 62 Ventilation Rates for 1999 and 2001

Although some players in DCV point out that CO_2 levels may not be an accurate indicator of occupancy (e.g., Damiano 2004), most proponents have advocated the Ventilation Rate Procedure (Murphy 2002, Carrier 2001). ASHRAE's Interpretation 62-2001-34 for Standard 62-2001 explicitly demonstrates how DCV can adhere to the Ventilation Rate Procedure (ASHRAE 2002b).

9.3.2.1 Implementation of DCV

The essential components in implementing DCV are (U.S. 2004):

- Installing CO_2 sensor(s) in zone(s) (and maybe outdoors[124]) and connecting the CO_2 sensor output to the DCV control board;
- Enabling modulation of the OA damper to proportionally modulate the delivery of OA, and
- Installing a DCV control board to control the OA intake rate based on CO_2 sensor readings.

DCV operation depends on the location of the indoor and outdoor CO_2 sensors. Because outdoor CO_2 sensors have to withstand a wider range of conditions and increase system cost, system designers often substitute a conservative estimate of the OA CO_2 concentration for real-time outdoor CO_2 measurements. To decrease installation costs, the CO_2 sensors are sometimes placed in the return air ducts, but sensors installed in the occupied zone of the occupied space (i.e., at head level or lower) are preferred because it correlates better with actual space conditions (Carrier 2001). CO_2 sensors based on non-dispersive infrared (NDIR) detection are the most common, but photo-acoustic sensors also exist (Carrier 2001). For the prevalent NDIR sensors, sensor calibrations last three to five years and sensor usually have a range from 0 to 2,000 ppmv (Telaire 2004, Texas Instruments 2004, Zebrick 2004). Some packaged rooftop and air handling units come with digital control boards that are DCV-ready, which decreases the cost of implementing DCV.

DCV operation controls the amount of OA introduced into a space based on the difference between indoor and outdoor CO_2 levels, dCO_2. In addition, building operators need to establish the dCO_2 equilibrium anchor point, i.e. the target dCO_2 level to be maintained by the ventilation system. Selection of the anchor point, e.g., 700ppm, depends on the desired OA ventilation rate and the anticipated occupant activity (which influences CO_2 generation rate per person; Carrier 2001). Although HVAC system design impact the control details[125], the general operation of DCV can be summarized as using the measured dCO_2 level to modulate an OA damper and/or ventilation fan to vary the OA intake rate to maintain the target dCO_2. Table 9-11, summarizes the three primary control strategies and Figure 9-4 graphically depicts their response.

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[124] An outdoor sensor measures the ambient level of CO_2 concentration and occupancy is estimated based on indoor CO_2 rise relative to the ambient level.

[125] Carrier (2001) discusses the nuances of DCV implementation for VAV and multi-zone systems.

Table 9-11: DCV Control Strategies (based on Carrier 2001)

Strategy	Description	Characteristics
Set Point	- OA rate undergoes a step function increase when dCO_2 concentration approaches the equilibrium anchor point - OA rate returns to baseline levels when dCO_2 falls a certain amount below the equilibrium anchor point, the OA rate	- Only for single-zone systems - Often used in facilities with high occupant densities that quickly reach peak levels (e.g., theater) - Simple control approach
Proportional	- OA rate begins to increase when CO_2 concentration rises to ~100-200ppm above OA CO_2 levels - Increase inversely linearly proportional to dCO_2 level - Maximum OA intake rate occurs at CO_2 equilibrium anchor point.	- Works well for most applications
Proportional-Integral	- Similar to proportional, but OA rate based on dCO_2 level and the time rate of change of dCO_2	- Highly responsive to changes - Provides superior energy savings and comfort - More sophisticated, complex control algorithm

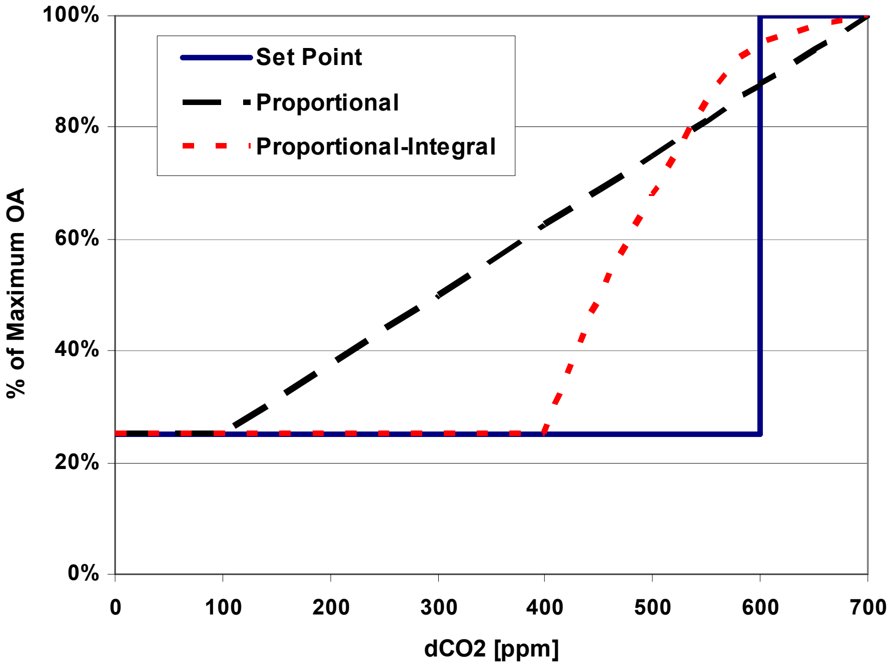

Figure 9-4: Illustrative Responses of DCV Control Strategies (based on Carrier 2001)

9.3.2.2 How and When DCV Saves Heating and Cooling Energy

DCV saves the most energy in applications with highly variable occupancy and extreme weather conditions. Long periods of low occupancy provide large opportunities to reduce the OA intake rate and thus save energy. If the weather is moderate, then the energy expended to condition the OA is minimal. Some building types and climates that fulfill one or both of these criteria are:

- *Theaters*: the average occupancy of a movie theater during open hours is 15% of its design capacity (Houghton 1995, Carrier 2001, Architectural Energy 2003),
- *Auditoriums / Public Assembly,*
- *Houses of Worship,*
- *Gyms,*
- *Restaurants (food service),*
- *Retail,* and
- *Southeast United States*: high cooling loads and high humidity.

During the cooling season, DCV control should be integrated with economizer function. There may be periods when OA can provide cooling in lieu of mechanical cooling, so it may be necessary to override the DCV system and allow high OA intake rates to take advantage of economizing during periods of low occupancy (Brandemuehl and Braun 1999).

9.3.2.3 Status of DCV

Although DCV is currently available and widely promoted (e.g., Carrier 2001, Murphy 2002), low levels of CO_2 sensor sales (BCS Partners 2002) suggest that it has a very small market share. School districts are one of the largest users of DCV for its ability to monitor indoor CO_2 concentrations. Geographically, the Northeastern region of the country appears to make greater use of DCV (Zebrick 2004). Due to the cost of DCV (especially for retrofits) and the continued concern over ASHRAE 62-2001, contractors usually only install DCV when specified by the building owner (Zebrick 2004). CO_2 sensors, a major cost component of DCV, have steadily improved in reliability and cost over the last ten years.

The future of DCV is being led by developments in CO_2 sensors and the evolution of codes and standards, in particular ASHRAE 62-2001. Several government agencies and relevant organizations are planning on encouraging or mandating DCV. For example, CO_2 monitoring and control can provide points for the indoor environmental quality portion of LEED 2.1 scoring for green building design (Carrier 2001). There is a proposal to modify the Oregon Building Code (NR-HVAC-7) to require HVAC systems to include provision for DCV during periods when spaces are only partially occupied (U.S. 2004). The California Building Standards Code was amended in June 2001 to require CO_2-based DCV in some high-density applications during periods of partial occupancy. The California Title 24 building code also has provisions for DCV (Schell 2001, Architectural Energy 2003). From 1997 to 2001, International Mechanical Code (IMC) has included provisions for DCV (Schell 2001). ASHRAE 90.1 requires CO_2 sensors for DCV in high-density applications (U.S. 2004).

9.3.3 Performance Benefits

The CO_2 sensors used for DCV may be the first sensor installed for a building owner to check ventilation effectiveness. Even without modulating the OA intake rate, the CO_2 sensors may detect inadequate fixed ventilation rates, which can result in poor IAQ. The DCV system's CO_2 sensors may also detect overventilation, in which case cooling loads may exceed the cooling system's capacity on very hot days. Both underventilation and overventilation[126] may cause decreases in IAQ and/or occupant comfort.

A building owner can use the CO_2 sensors that come with DCV to verify ventilation in the building space regardless of whether the outdoor air intake is modulated or fixed. Recording CO_2 sensor readings may also be valuable as proof of adequate ventilation in an IAQ lawsuit (Houghton 1995). In multizone applications, DCV can transfer ventilation from under-occupied zones to fully-occupied zones. DCV readily adapts to changing ventilation requirements, e.g., if the metabolic rate of occupants exceeds that assumed in ASHRAE 62 standard, DCV can immediately compensate by increasing the OA intake rate (Carrier 2001). In practice, actual total supply airflow often varies significantly with damper position (Braun et al. 2003), i.e. a set damper position does not guarantee proper ventilation rate. CO_2 measurements of both indoor and outdoor can ensure that spaces receive sufficient OA and, if recorded (e.g., by an EMCS), can enable documentation to this effect. Besides verifying ventilation, CO_2 sensor readings may also help detect and compensate for faulty economizer dampers (see Section 8.5, "Dampers Not Working") by comparing the difference between indoor and outdoor CO_2 levels with those predicted by the damper position (Carrier 2001).

School districts are one of the largest users of DCV because they want to monitor IAQ via CO_2 readings (Zebrick 2004). In field tests of DCV in California modular schoolrooms, DCV provided lower CO_2 concentrations than a fixed ventilation configuration determined by ASHRAE Standard 62-1999 (no economizer). The "Factory Standard" installation of the OA damper position probably resulted in the damper being set too far closed. With the "Factory Standard" installation CO_2 levels exceeded 1,200 ppm for 60% of the occupied hours (1,000 is typically the maximum acceptable level). The 1,200 ppm level also violated California's own Title 24 requirements (Braun et al. 2003). Therefore, it is possible for DCV to yield superior IAQ to more conventional fixed ventilation rate configurations. In a case study of an office building in Birmingham, Alabama, the DCV system showed that the previous fixed ventilation system provided more than enough ventilation to the space, so the DCV system reduced the overall OA intake. As a result, tenants no longer complained of high humidity because the air-conditioning system could finally dehumidify the smaller intake rate of humid outdoor air. In this case, DCV *improved* occupant comfort as well as saved energy (U.S. 2004).

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[126] Over-ventilation can result in excessive indoor humidity levels that can cause IAQ problems (e.g., mold growth) and occupant discomfort.

9.3.4 Energy Savings Potential

DCV reduces the energy required to condition outdoor air and, in variable air volume systems, also reduces blower energy consumption. Most existing energy savings data reflect simulations based on the older ASHRAE 62-1999 standards for ventilation. The most comprehensive studies performed simulations (Brandemuehl and Braun 1999, Mercer and Braun 2005) of several different ventilation strategies for four building types with CAV systems in twenty different US cities. A recent study performed simulations and field tests of DCV in restaurants, modular classrooms, and retail drug stores in inland and coastal California (AE 2003).

Although the simulations summarized in Brandemuehl and Braun (1999) varied airflow rates based on the 1989 version of ASHRAE Standard 62, several key conclusions from their study still hold, including:

- DCV saves more cooling energy in climates with fewer opportunities for economizer cooling, e.g., hot and humid climates;
- DCV can achieve large reductions in heating energy consumption in cold climates;
- DCV saves more energy in buildings with low ratios of average to design occupant density;
- DCV operation should be coordinated with air-side economizer operation such that it does not interfere with economizer energy savings;
- DCV often can realize greater reductions in heating energy than cooling energy, particularly in colder climates, and
- Greater heating energy savings (on a percentage basis) occur in buildings with large variability in occupancy and relatively high internal gains, i.e., where OA accounts for a larger portion of heating loads.

The cooling energy savings for DCV varied between 6 and 22%, depending on location and building type[127]. Office spaces also showed less energy savings than schools or retail stores. A simulation of an office building in the southeastern U.S. found that DCV reduced cooling and heating energy consumption by about 10% and 9%, respectively. These predictions were based on ASHRAE 62-1999 (U.S. 2004). These more modest energy savings are appropriate for the warm, humid climate found in the southeast and for an office building with less variation in occupancy. DOE 2.2 simulations of a new school building design in Chicago found that DCV could reduce *total* building energy consumption by 5% (Olsen 2004). Assuming that heating and cooling account for about 40% of total energy consumption[128], DCV reduced heating and cooling energy consumption by about 12%.

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[127] They also calculated heating energy savings that, on a percentage basis, seemed extremely high in many cases (e.g., >90%).

[128] National data for educational buildings indicate that heating and cooling account for an average of 38% of total primary energy consumption and 50% of site energy (BTS 2003).

In general, case studies of field implementations of DCV tend to yield similar energy savings. One study evaluated the energy performance of DCV in three different building types (restaurants, schools, and retail stores) in two different climate zones in California. They used DCV with economizer control and DCV without an economizer. With the economizer, the return air CO_2 set point was 800 ppmv. With the economizer control off, there was a minimum damper position set that complied with ASHRAE standard 62-1999. Due to California's mild climate, they only reported cooling energy savings. Applied to a restaurant in Southern California, DCV could reduce cooling energy consumption by 6 to 23%[129], depending on the climate (Architectural Energy 2003). The same study also found, however, that DCV did not achieve appreciable energy savings in schools due to a relatively constant occupancy rate and the fact that the HVAC systems shut down during the evening, i.e. the only unoccupied period, rendering DCV relatively moot from an energy savings perspective.

In sum, the available data suggest that DCV can reduce both heating and cooling energy by about 10%, or about 0.3 quads natioanlly.

9.3.5 Cost

To evaluate the cost of implementing DCV, we assume that a non-DCV packaged unit has a manual damper without an economizer. Therefore, a DCV-capable packaged unit requires the addition of four components:

- A digital controller capable of modulating the OA damper based on a CO_2 sensor input and economizing conditions;
- An economizer that normally includes a variable-position OA damper;
- A CO_2 sensor for every 5,000ft^2 or zone (Carrier 2001), and
- Installation and maintenance of all new components, notably the CO_2 sensor(s).

A major HVAC manufacturer includes a DCV-ready controller with its economizer for an additional $500 to $600 on its 3- to 20-ton rooftop air-conditioning units (Osborn 2004). The digital controller often incorporates several optional features such as humidity control along with the DCV control. Therefore, obtaining the first two items costs approximately $500. The commonplace NDIR CO_2 sensors typically cost from $200 to $300 uninstalled. The guaranteed calibration period of the sensor is the main driver in the price (Telaire 2004). The less common photoacoustic CO2 sensors have a list price of $450 with a five-year guaranteed calibration (similar to the NDIR sensors). However, this particular sensor from MSA also includes a VOC sensing capability, and the manufacturer claims higher sensitivity and stability than the competing NDIR sensors (MSA 2004). The cost of CO_2 sensors will likely decrease in the future. CO_2 sensors became available rather recently, i.e., in 1992, and an estimated 60,000 sensors are sold annually for ventilation control in buildings (U.S. 2004); clearly, however, the potential market is much larger. As an example

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[129] The energy savings are predicted from field test data acquired for only a fraction of a year. Unfortunately, the study did not collect sufficient data to evaluate the performance of retail stores.

of how the expanding sales volume has allowed the unit cost of sensors to fall, the unit cost of CO_2 sensors dropped from $400 to $500 a few years ago to $200 to $250 today (US 2004).

The costs of all four items can vary widely depending on the existing control system, ease of access to the space, etc. The installed cost of a new DCV system equals about $600 to $700 per zone. For retrofit applications, the installation costs are $700 to $900 per zone with existing DDC programmable controller and $900 to $1,200 per zone without DDC controls (U.S. 2004). The cost will also be higher when installing the CO_2 sensor in the space rather than a return air duct because of the difficulty in wiring the sensor to the controller on the rooftop unit. In a DCV study in California, installation time for a sensor in the return air duct was assumed to be four hours (AE 2003). That study also assumed a $900 cost premium for each rooftop unit.

The many factors influencing cost and energy savings such as occupancy schedule, climate, difficulty of installation, etc., complicate the development of cost and SPP estimates. Based on the literature, the assumed cost premiums were $900for a 5-ton unit, $1100 for a 10-ton unit ($200 more for one additional CO_2 sensor), and $1500 for a 20-ton unit ($600 more for three additional CO_2 sensors). Table 9-12 presents estimated SPPs for illustrative heating and cooling energy saving levels, assuming that an average RTU consumes $140/ton/year for cooling and $144/ton/year for heating[130] (ADL 1999, ADL 2001).

Table 9-12: Estimated SPP for DCV in Different RTU Implementations

Unit Size [tons]	Annual Heating / Cooling Savings[%]			
	5% / 10%	10% / 10%	15% / 10%	20% / 20%
5	9.3	6.8	5.4	4.0
10	6.2	4.6	3.6	2.6
20	4.7	3.4	2.7	2.0

The heating and cooling savings ranges used in Table 9-12 reflect the general range of energy savings percentages found in most DCV evaluations (excepting Brandemuehl and Braun 1999, which reports much higher savings; see Section 9.3.4). Table 9-12 indicates that DCV may have reasonably attractive SPP when used with larger systems and in applications that result in higher heating and cooling savings (see discussion in Section 9.3.4). Importantly, these results likely underestimate the economic attractiveness of DCV in buildings with high demand charges, which increase the cost of cooling energy consumption.

Overall, these findings are broadly consistent with several studies that estimate simple payback periods (SPP) in the two to four year range. For example, the SPP ranged from 2.9 to 6.5 years for a children's play area in a fast food restaurant based on simulation results

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[130] Based on an electric rate of $0.08/kWh and a gas cost of $6/MMBtu.

(Braun et al. 2003). In a case study of an office building in the Southeast, the SPP was predicted to be 2.2 years (US 2004). A major HVAC manufacturer claims SPP ranges from a few months to two years (Carrier 2001).

9.3.6 Barriers

Potential IAQ liability issues faced by HVAC system designers and sensor cost and calibration issues pose the greatest barriers to greater DCV implementation.

Most building operators are more concerned about IAQ than building energy savings (Zebrick 2004). Consequently, HVAC system designers and building owners typically ensure that their systems provide sufficient OA (e.g., per the prescriptive method of ASHRAE 62-2001 or using CO_2 sensors to validate OA levels) before they consider implementing DCV for energy savings. The numerous addenda and interpretations to ASHRAE 62 have, in many cases, increased confusion about whether or not properly implemented DCV provides sufficient IAQ. Instead of allaying concerns about DCV implementation, this may have increased concerns about designer liability for IAQ problems that arise in buildings using DCV (Zebrick 2004). As a result, several parties have suggested amendments to ASHRAE 62 to clarify the allowance of DCV (Persily et al. 2003). HVAC system designers must also adhere to other building codes besides ASHRAE 62, which may place additional requirements or restrictions on DCV, including California's Title 24 (Persily et al. 2003) and the International Mechanical Code 2003 (Damiano 2004). In sum, satisfying building standards and codes take precedence over DCV implementation.

Despite significant advances in CO_2 sensor development, laboratory experience at LBNL with DCV indicates CO_2 sensor drift is an issue (U.S. 2004). Despite the fact that the published calibration period of a CO_2 sensor is three to five years, one sensor vendor recommends annual calibrations (Zebrick 2004). In addition, a skilled and well-trained building maintenance staff is essential to maintain sensors and associated controls (U.S. 2004). This incurs costs both to maintain sensor calibration and train the staff.

CO_2 sensors comprise a significant (roughly one-third) fraction of the cost of implementing DCV. Unfortunately, multizone applications require multiple CO_2 sensors for best performance (Persily et al. 2003), and more costly wall sensors are preferred to sensors in the return air duct for better CO_2 sensing accuracy (U.S. 2004). All of these guidelines increase the cost of DCV implementation.

9.3.7 Technology "Next Steps"

Although DCV has entered the buildings market, potential users of DCV need unambiguous information that DCV can maintain acceptable IAQ and will not violate ASHRAE Standard 62 when properly applied to gain a large market share. Only after overcoming this regulatory/clarity hurdle can rigorous case studies that evaluate the cost effectiveness of DCV and development of lower-cost, high-reliability CO_2 sensors realize a widespread benefit for DCV.

1. *Clarification of the ASHRAE 62 Standard*: Developing a clear statement of what a DCV must do to satisfy IAQ requirements – or, even better, how a DCV system can provide *ipso facto* air quality – is essential to overcome the liability concerns raised by HVAC designers and contractors. DCV will have a very difficult time succeeding if this
2. *Case Studies*: Rigorous case studies of DCV implementation using the new ASHRAE Standard 62 specifications are needed to quantify its costs and benefits (energy savings and IAQ levels [including pollutants, not just CO_2]), particularly in colder climates where DCV may yield greater energy savings. Ultimately, these can yield design and implementation guidance. This will increase the confidence of potential users that DCV can achieve energy savings while maintaining IAQ.
3. *Sensor Development*: Development of low-cost, accurate CO_2 sensors that require infrequent maintenance and calibration can enhance the up-front and life-cycle economics of DCV.

9.3.8 References

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9.4 Duct Leakage Diagnostics

9.4.1 Summary

Many duct systems in commercial buildings have high levels of duct leakage, i.e., at least 10% of duct flow. Duct leakage in ducts located outside the building’s thermal barrier transfer heated or cooled air to the outdoor space, which increases heating and cooling energy consumption. Because less heat is delivered to the target spaces, duct leakage also causes the blowers in variable air volume (VAV) systems to run “harder” to deliver the required heating or cooling to the conditioned space. Nationally, duct leakage increases commercial building HVAC energy consumption by 0.15 to 0.4 quads. Several ways exist to reliably measure duct leakage in residences, but the greater complexity of duct systems in commercial buildings limits their applicability. Two techniques have recently been developed that may become tools to measure the leakage of commercial duct systems. One compares highly accurate volumetric flow measurements in the main trunk duct or large branch ducts with that through the registers to quantify duct leakage. The other technique, which applies only to VAV systems, uses pressure and flow measurements and mathematical modeling of the duct system to develop a qualitative (e.g., good, marginal, poor) assessment of duct leakage. Both approaches require field evaluation to confirm their ability to accurately measure duct leakage. In addition, the comparative flow measurement technique would benefit from development of a commercial test kit to significantly reduce test equipment costs.

A lack of knowledge about the prevalence and energy impact of duct leakage would also likely impede widespread use of duct leakage diagnostics. Furthermore, it is not clear that many owners would choose to fix leaky ducts in existing buildings because the cost of aerosol-based (or another approach) duct sealing far exceeds that of detecting duct leakage. Consequently, the diagnostic techniques may be more successful as building commissioning tools, i.e., it would enable commissioning agents to evaluate duct leakage while the ducts are still accessible for application of mastic (to seal the ducts).

Table 9-13: Summary of Duct Leakage Diagnostics

Characteristic	Result	Comments
Technology Status	Advanced	Current for residential, advanced for Commercial
Systems Impacted by Technology	All ducted HVAC systems,	Includes Rooftop Units (RTUs), Unitary Split Systems, and Central Station Air Handling Units
Readily Retrofit into Existing Buildings and Systems	Yes	Approaches under development are for one-time measurement rather than continuous monitoring. No major building alterations required.
Relevant Primary Energy Consumption [quads]	3.1	All heating, cooling, and parasitic energy associated with ducted central and packaged HVAC systems
National Technical Energy Savings Potential [quads]	0.15 to 0.4	Based on Phase I of this Study.
Non-Energy Benefits	Potential for reduced fan noise.	
Approximate Simple Payback Period [years]	2.5 to 15+	Varies with building type/energy consumption, duct leakage magnitude
Key Economic Barriers	Cost of performing test and, for existing systems, sealing ducts	Labor costs significant for detection via LBNL approach; aerosol-based duct sealing costs several times more than detecting high duct leakage levels
Key Non-Economic Barriers	• Awareness of duct leakage and testing • Controls-based approach only applies to VAV systems	
Key Enabling Technologies	Low-cost CO_2 sensors.	
Notable Developers of Technology	Lawrence Berkeley National Laboratory, Federspiel Controls	
Peak Demand Reduction?	Yes	Reductions of VAV blower power and cooling energy consumption
Most Promising Applications	HVAC systems with extensive ductwork; the Federspiel Controls diagnostic approach applies only for VAV systems with pressure-independent terminal unit control.	

Characteristic	Result	Comments
Technology "Next Steps"	• Commercialize duct leakage diagnostic technologies • Field evaluations of duct leakage energy savings • Increase awareness of duct leakage and duct leakage detection approaches within the industry • Train test and balance contractors to carry out test procedure	

9.4.2 Background

A range of duct leakage diagnostic tests described in the literature and by system practitioners, including their applicability and status, is summarized in Table 9-14 below. Most of the tests are oriented towards residential air-conditioning systems and much of the work to examine their applicability has been done in residences. None of the tests listed is, however, a viable continuous diagnostic tool.

Table 9-14: Duct Leakage Diagnostic Test Summary

Test Procedure	Reference(s)	Applicability	Status
House Pressure Test	6,7	Residential	Current
Nulling Pressure Test	6,7	Residential	Current
Duct and House Pressurization	6,7	Residential	Current
Irvine Quality Plus Duct Pressurization	7	Developed for Residential; Commercial use possible with modifications	Current
Tracer Gas	6,7	Residential, Commercial	Current
ASTM E1554 A: Blower Door Subtraction	1,6	Residential	Current
ASTM E1554 B: Duct Pressurization	1,6	Residential	Current
Delta Q	5,6	Residential	New
SMACNA Duct Pressurization	4	Residential, Commercial	Current
LBNL Proprietary Test Method for Commercial Duct Systems	8	Commercial	Advanced
Federspiel Controls InCITe^{TM}	9	VAV Systems with Pressure-Independent Terminal Boxes	Advanced

References: (1) ASTM 2003 (2) Diamond et al. 2003; (3) Fisk et al. 2000; (4) SMACNA, 1985; (5) Walker et al. 2002; (6) Walker et al. 2001; (7) Walker et al. 1998; (8) Wray 2004.

The higher complexity of commercial buildings and their HVAC systems makes many residential leakage tests unsuitable for them. While the SMACNA Duct Pressurization test, which is used for commercial as well as residential systems, gives an indication of duct system tightness, it does not provide a good indication of leakage airflow during system operation. Leakage during operation depends on duct pressure level, which varies throughout the duct system. VAV systems have a distinct difference between duct pressure levels upstream and downstream of terminal units; this further complicates determination of duct leakage during operation.

Lawrence Berkeley National Laboratory (LBNL) developed a proprietary duct leakage test that has not been commercialized (Wray 2004). This test involves measuring the duct flow at the trunk or a major duct branch and the air flow exiting all diffusers served by the system or branch (see Figure 9-5). The leakage equals the difference between the duct measurement and the sum of the diffuser measurements. A CO_2 tracer gas-based procedure for measurement of trunk or branch flow has been developed. It involves cutting ¾" holes into the duct wall at the location of the flow measurement, inserting a tracer gas injector with circulation fans to enhance mixing, and installing a concentration measurement probe not far downstream of the tracer gas injection point. Subsequently, the injector introduces CO_2 gas in 30- to 60-second bursts. Testing has shown the method to provide flow measurement accuracy of 2%. Flow hoods measure the diffuser flows and LBNL testing indicates that properly designed flow hoods can achieve a similar 2% measurement accuracy. The developers estimate that the equipment required to carry out this procedure (if manufactured by a diagnostic test equipment vendor) would cost approximately $5,000 (Wray 2004).

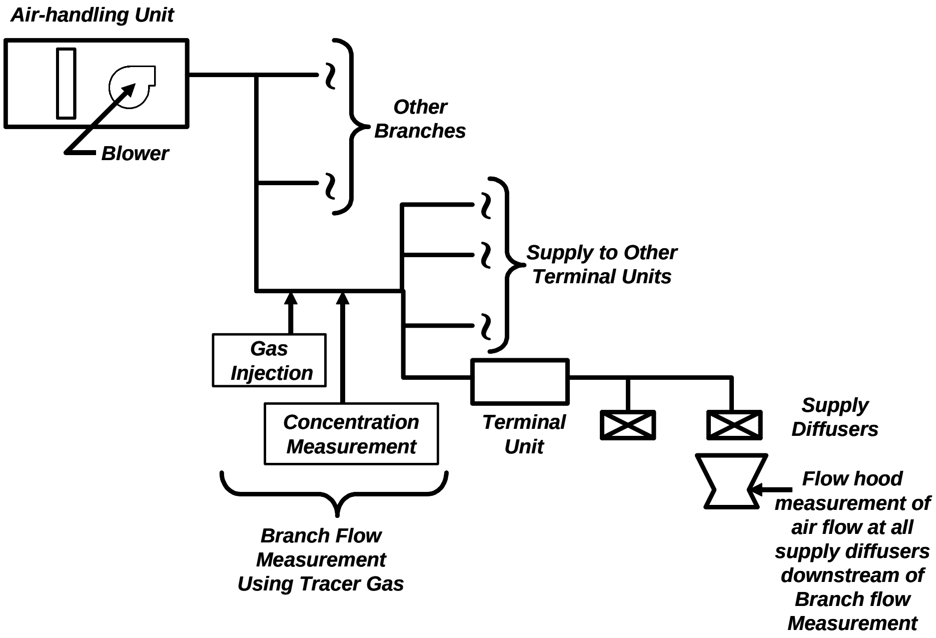

Figure 9-5: Illustration of LBNL Duct Leakage Test Method

The Federspiel Controls InCITe^{TM} procedure was developed to provide an indication of critical duct pressure for Variable Air Volume (VAV) systems (Federspiel 2004). Determination of this and other parameters enables implementation of their Static pressure Adjustment from Volume flow (SAV) approach to control VAV static pressure reset. VAV system blowers are controlled to maintain a duct pressure level sufficient to enable VAV terminal units to control the air flow delivered to the zones they serve. Many VAV systems maintain a constant pressure level that exceeds the minimum duct pressure level required for a terminal unit to maintain control, called the critical pressure, all or nearly all of the time. Static pressure reset control can allow reduction of duct pressure at part load. If the pressure is too low, i.e., falls below the critical pressure, one or more of the terminal units will have its damper wide open. As a result, insufficient air flow will be delivered to the unit's zone and the zone temperature will rise or fall. The Federspiel Controls SAV control uses an empirical relationship between supply flow and duct static pressure to implement static pressure reset. The InCITe^{TM} procedure assumes a simple physical model of the pressure-flow relationship that accounts for duct leakage upstream of the terminal units as well as load changes during the procedure. The procedure requires measurement of system total air flow and duct pressure and uses a series of measurements made under varying duct pressures. It analyzes the measurements to determine the SAV model parameters.

Figure 9-6 depicts illustrative InCITe^{TM} test results for a VAV system. At high duct pressures, the terminal units have enough pressure to achieve their setpoint flow levels. The total flow drops off only slightly as duct pressure decreases, since the terminal unit dampers can open wider to maintain flow level. When the terminal units reach their 100% open position, i.e., the system reaches critical pressure, further reduction in duct pressure results in significant reduction in air flow (see Figure 9-6). Air leakage upstream of the terminal units influences the slope of the flow/pressure line above the critical pressure (Federspiel 2004).

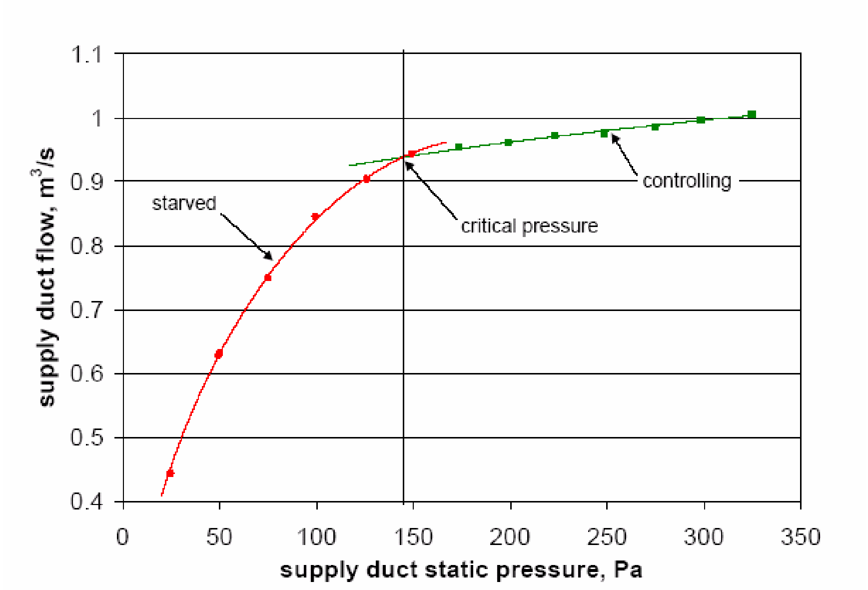

Figure 9-6: Example of Application of InCITeTM Procedure to a VAV System (from Federspiel 2005)

Laboratory evaluation of the test procedure indicates that the leakage estimate derived from the procedure has moderate accuracy, indicating it provides an indication of leakage level but not an accurate measurement of leakage as a percentage of total system flow. One limitation of this method as a duct leakage diagnostic is that it only evaluates leakage upstream of terminal units in VAV systems with pressure-independent terminal units. The developers plan future field testing of the InCITe^{TM} procedure to validate its capability as a diagnostic method for duct leakage for VAV systems.

The potential energy savings associated with duct leakage diagnostics depend on identification of high duct leakage and subsequent implementation of duct sealing. Reduced duct leakage has the potential to decrease cooling energy, heating energy, and blower energy. In practice, the energy savings potential depends on the particular status of each system, including the leakage level, whether the leakage occurs internal or external to the building, length of ductwork, etc. The standard way of sealing leaks is to reapply duct sealing mastic. This is, however, an expensive and tedious process, and it may be impossible for some sections of ductwork located in inaccessible places. Aerosol sealing of ductwork developed for residential duct systems has also been attempted, to a very limited extent, in commercial building systems. Further application of this approach to commercial systems is needed to establish its feasibility and cost characteristics for these applications.

The status of duct leakage diagnostic approaches is developmental, particularly for commercial systems. While contractors have used duct pressurization approaches (i.e. the SMACNA test) for many years, tests that provide a good indication of operating condition leakage remain at the developmental stage. Furthermore, approaches suitable for regular in situ monitoring of duct leakage characteristics have yet to be even proposed.

9.4.3 Performance Benefits

The primary non-energy benefit of duct leakage diagnostics depend on potential reductions in blower speeds after fixing leaks. The related benefits include:

- Reduce blower noise, and
- Increased blower/motor/drive life and reduced maintenance.

9.4.4 Energy Savings Potential

The energy savings potential of duct leakage diagnostics depends on the number of duct systems that have high leakage and the number of these that are sealed. The Phase I estimate of energy waste associated with duct leakage equals 0.15 to 0.4 Quad. This represents a maximum amount of energy that duct leakage diagnostics could save. Actual savings would be limited by the number of building owners/operators that take advantage of duct leakage diagnostics technology, the number leaky duct systems that are fixed, and the number of duct systems with low to moderate leakage that are not cost effective to seal.

9.4.5 Cost

The LBNL duct leakage diagnostics approach costs more than the Federspiel controls InCITe^{TM} approach, but has higher accuracy and broader applicability. The following discussion focuses on the LBNL approach.

The cost of the LBNL duct leakage test consists of the labor cost to carry out the test and, to a lesser extent, the cost of the test equipment. A reasonable estimate of labor time to carry out the test for a given duct section is two hours each for two people. Assuming that the average duct section serves 5,000ft^2 and that labor costs $50/hour, labor cost represents about $0.04/ft^2. For comparison sake, amortizing the $5,000 equipment cost over the course of 100 tests, the equipment cost yields an additional cost of about $0.01/ft^2. When including overhead costs and variance in the estimates, the diagnostic cost could be in the range of approximately \$0.05 to \$0.10/ft^2. This reflects a future scenario with commercially available diagnostic equipment kits based on the LBNL diagnostic (purchased from a diagnostic equipment vendor) are used by contractors experienced in the approach, using properly trained technicians.

Additional costs for sealing a leaky duct system would be \$0.40 to \$0.50/ft^2, assuming use of an aerosol duct sealant (Modera 2004) that may represent the best approach to seal ducts in existing buildings. That is, the cost of fixing leaky ducts in existing buildings is several times greater than the cost to diagnose the leaky ducts. For new construction, i.e., after carrying out a leakage check as part of commissioning, re-application of mastic would be the preferred approach. In this case, the cost probably would not be a factor, since the commissioning agent would not approve the “faulty” duct system until testing indicated that it had acceptable leakage levels.

The potential energy use impact of duct leakage is discussed in Phase 1 of this report (Section 8.4) and represents 3 to 9 percent of energy use for heating, cooling, and parasitics (blowers, fans, pumps, etc.) in commercial buildings. The average energy cost for commercial buildings varies from \$0.35/ft^2 to \$2.00/ft^2, depending on building type (assuming average utility costs of \$0.08/kWh for electricity and \$6/MMBtu for fuel; ADL 2001). This translates into average energy cost savings associated with elimination of excess duct leakage between \$0.015 to \$0.20/ft^2. In sum, the simple payback period for duct leakage diagnostics and duct sealing could be as low as 2.5 years, but would exceed 15 years for buildings with the least energy use and/or low levels of duct leakage.

9.4.6 Barriers

Duct leakage diagnostic techniques that provide estimates of duct leakage during system operation are not yet generally available. The Federspiel Controls InCITe^{TM} approach has not be available for very long, and several factors hamper its general adoption: (1) Only a single, small vendor currently offers the product; (2) It primarily addresses system tuning for static pressure reset control rather than duct leakage diagnostics, and (3) It is suitable for VAV systems with pressure-independent terminal box control. Information about the LBNL approach has not yet been published, nor has the approach been commercialized.

At present, very little awareness exists about the prevalence and energy impact of duct leakage and most building personnel have little or no appreciation of the potential benefit of duct leakage diagnostics. Consequently, it is doubtful that there would presently be a substantial market for the diagnostics if commercialized. Duct leakage diagnostics also suffer a general issue with diagnostics, that is, that resolution of the diagnosed problem, not the diagnostics, save energy. Some systems will not have significant levels of leakage, in which case the diagnostics do not save energy and money. Even when a system does have high leakage levels, it may require costly aerosol sealants to alleviate the problem. The cost of aerosol-based duct sealing equals a significant fraction (roughly 1/3rd or more based on Cler et al. 1997, BOMA 2001) of most building O&M annual budget, which may prohibit many building operators from fixing the duct leakage issue. Furthermore, the fact that duct leakage diagnostics are not considered part of standard duct installation practice may be a market barrier, i.e., people assume that the contractors installing the ducts have verified the quality of the installation so that the ducts do not require diagnostic evaluation. This parallels a similar barrier to commissioning of new buildings, where people assume that the contractors have established that the building systems function properly, which obviates the need for commissioning.

9.4.7 Technology "Next Steps"

Commercialized duct leakage diagnostics could play a valuable role, e.g., as part of a commissioning process, to ensure that ducts in new buildings have low leakage rates. Several "next steps" exist to further the development of commercially viable duct leakage diagnostic testing. They can, however, only have a very limited role in reducing duct leakage in existing buildings because they do not address the primary barrier to reducing duct leakage, i.e., the high cost of remedying duct leakage in existing buildings.

1. *Field Evaluations of Duct Leakage Energy* Savings: Very limited data exists to quantify the per-building energy cost impact of duct leakage. Rigorous evaluations of the energy impact of duct leakage in commercial buildings, i.e., via longer-term monitoring and/or detailed simulations, will help building personnel grasp the energy impact (and, hence, the benefit) of detecting and reducing duct leakage.
2. *Diagnostic Test Procedure Field Demonstration*: Further demonstration development of the LBNL and Federspiel Controls leakage diagnostic tests to evaluate their viability and accuracy.
3. *Duct Leakage Test Procedure and Equipment Suite Development*: Development, testing, and validation to determine techniques with sufficient accuracy for use in duct leakage diagnostics testing, as well as commercialization of low-cost procedure(s) to detect and quantify duct leakage.
4. *Test Procedure Information Dissemination*: Presentation and documentation of the approach and test results to engineers and practitioners to establish credibility, increasing awareness among building owners and operators, engineering firms, and contractors, and training of test and balance contracting firms to carry out the procedures.

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9.5 HVAC Sensors – Temperature, Humidity, and Pressure

9.5.1 Summary

Temperature, pressure, and humidity sensors are of primary interest in HVAC systems. Of these, temperature and pressure sensors are stable and reliable, whereas humidity sensors are more susceptible to long-term drift in accuracy. Installation errors (sensor location, wiring, software, hardware) can be more significant than sensor-specific errors, and can cause large and highly variable errors in the resulting sensor data (CEC 2003).

Advances in MEMS technology and the related economies of scale may contribute to lower HVAC sensor prices while, in some cases (e.g., humidity sensors), improving performance. Wireless technologies are evolving rapidly not only in HVAC but in many industries and markets, but lack of a single standard for HVAC systems has led to a proliferation of products that use different frequencies, transmission modes, and data communication protocols. Wireless technologies bring greatest value for installations with prohibitive hard-wiring costs, e.g., the installation of additional sensors in existing buildings. Although wireless systems have come to market, best implementation practices are not well known. Dissemination of thorough field studies and demonstration projects to evaluate the costs and benefits of wireless sensor technology and identify best practices would buttress building owner and control contractor familiarity with and confidence in wireless building controls and increase their rate of deployment.

Table 9-15: Summary of HVAC Sensors

Characteristic	Result	Comments
Technology Status	Current / New	Some wireless and MEMS-based sensors have come market
Systems Impacted by Technology	All Building and Equipment Controls	
Readily Retrofit into Existing Buildings and Systems	Yes	
Relevant Primary Energy Consumption [quads]	5.0	All HVAC and large refrigeration systems
National Technical Energy Savings Potential [quads]	N/A	Sensors enable energy savings but do not, per se, reduce energy consumption
Non-Energy Benefits	Multiple	Applications specific, e.g., sensors for diagnostics could reduce maintenance and replacement costs, additional temperature sensors could enhance occupant comfort
Key Economic Barriers	Installed cost of sensors	Humidity sensors are notably costly
Key Non-Economic Barriers	Stability of humidity sensors; communications infrastructure for measurements; indirect link between sensors and energy savings	
Key Enabling Technologies	MEMS, wireless communications (includes very low-power sensors and communications, power-scavenging, standard protocols)	
Notable Developers of Technology	Sensors: Numerous, including major building controls manufacturers. Wireless Sensors: Honeywell, Inovonics, Kele, Point Six Wireless Networks: Dust Networks, Ember, Inner Wireless (teamed with Johnson Controls), Kiyon, Millenial Net Power Scavenging: U.C. Berkeley	
Peak Demand Reduction?	Potentially	To the extent that additional sensors enable control and diagnostic approaches that reduce peak demand
Most Promising Applications	• Equipment-level diagnostics (larger chillers, larger RTUs) • Wireless networks: Adding sensors for greater control or diagnostics functionality to existing buildings	
Technology “Next Steps”	• Thorough case studies of wireless sensor implementations • Identification, documentation, and dissemination of wireless sensor system best practices	

9.5.2 Background

Sensors measure the physical conditions of HVAC equipment, indoor spaces, and the surrounding environment. This section addresses sensors used to provide input to HVAC systems for HVAC system control. Temperature sensors are distinguished from conventional thermostats, i.e., switches that operate based on both the surrounding temperature and the user-determined setpoint. This chapter does not explicitly address room thermostats or simple "on/off" type switches.

Three sensors of primary interest in commercial building HVAC systems are temperature, pressure, and humidity. Common locations for these sensors are mechanical equipment, conditioned spaces, building piping or ducts, and outdoors (see Appendix A). Sensors typically consist of a sensing element that senses a physical property, additional electronic circuitry that converts signals from the sensing element into a useful output signal, and an enclosure that houses and protects the element and electronics. Many packaged electronic sensors output either 4-20mA or 0-10V analog signals that are proportional (or corrected to be proportional using hardware or software) to the sensed condition. This output signal is observed and processed by a human system operator, a controller, or an energy management and control system (EMCS) to enable appropriate HVAC system control actions. Temperature sensors account for the vast majority (about 75%) of building controls sensors sold (BCS 2002).

Sensors used in HVAC systems must provide adequate performance in several ways:

Sensitivity: Provide a measurable change in its output signal for meaningful changes in the sensed environment.

Accuracy and Resolution: Sufficient accuracy and resolution to enable the desired accuracy and resolution in the HVAC system control.

Responsiveness: Its response time must be shorter than the response time of the system to which the sensor provides input.

Low Noise Levels: Sensor electronics (that generate sensor output signals) need to have electronic noise levels that do not interfere with the output signals.

Robust: Sensors also need to be robust, i.e., to maintain calibration and operate reliably for many years under a variety of environmental conditions.

Typically, the cost of the sensing element often accounts for a relatively small portion of the total package cost. All of the above requirements increase the total packaged sensor's price. Most packaged sensors, called transmitters[131], have end-user costs ranging from scores to a couple hundred dollars (see Table 9-22). Exceptions to this broad definition include resistance temperature devices (RTD) and thermistors. In this section, transmitters and resistance-based temperature devices (RTDs and thermistors) are also referred to as "sensors."

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[131] The use of the word "transmitter," while common in this context, must not be confused with the same word's use in discussions of wireless-enabled sensors.

Advances in sensor technology have begun to appear in HVAC systems. Continuing progress in the development of Micro-Electronic Mechanical Systems (MEMS) has influenced sensor development in a variety of applications, such as humidity and pressure sensors. Key to the potential benefits of MEMS technologies is the ability to manufacture many solid-state sensors on a single semiconductor wafer, which reduces cost. In general, MEMS sensors are low in price, small in package size and low in weight, and some technologies may offer increased accuracy or resistance to long term drift.

Research and manufacturing economies of scale from the automotive industry have benefited the HVAC market, as sensors designed for vehicle transmissions, air conditioning, and anti-lock brake systems have found application in higher-pressure refrigerant systems that use CO_2 and ammonia refrigerants (Franz 2003). Sensor advances in the automotive industry are in part due to incorporation of MEMS technologies, standardization of components and systems, and large sales volumes.

Wireless technologies intended to facilitate sensor deployment are entering the commercial building sensors market. Early wireless systems replaced wires on a one-for-one basis. Future systems hope to make use of features that provide robust connectivity and reduce installation cost and time, such as self-enabling and self-healing mesh networks (CABA 2004; Turpin 2004, Zebrick 2004) and seamless integration with commercial building HVAC networking standards such as BACnet (Wang and Nova 2004).

9.5.3 Current Sensor Technology

9.5.3.1 Temperature Sensors

Temperature sensors are highly robust, i.e., they can survive a wide range of environmental conditions and typically function properly for at least ten years. They tend to fail obviously (i.e., stop working completely) rather than degrade over time, which makes failures more detectable and reduces the likelihood of a bad sensor being left in service for long periods of time (Kele 2004a). Temperature sensors, depending on the type selected, can also be among the least expensive of sensors to purchase. Temperature sensors measure indoor, duct, and outdoor air temperatures, while immersion-type sensors measure water or refrigerant temperatures, e.g., for chilled water loops or hydronic heating systems. Typically, temperature sensors have an accuracy of ±0.5ºF or better, which suffices for most HVAC applications. Consequently, temperature sensor selection often comes down to its cost. Depending on how the temperature sensor has been configured to operate, its output may be a voltage or a current, or the sensor may present to the attached system a resistance that varies depending on temperature.

Table 9-16 summarizes temperature sensor measurement technologies and their major advantages and disadvantages. The two most commonly used temperature sensors, thermistors and RTDs both quantify temperature based on how the resistance of an element changes with temperature. RTDs typically have a linear relationship between temperature and resistance, and thermistors a non-linear relationship (DDC-Online 2004).

Table 9-16: Temperature Sensor Technologies and their Pros and Cons (based on CEC, 2003; DDC-Online, 2004)

Sensor Type	Advantages	Disadvantages
Thermocouple	• Inexpensive • Simple • Rugged • Widest operating range • Good for high temperatures • No external power supply required	• Nonlinear • Lowest accuracy of temperature sensors • Susceptible to noise • Long term stability low compared to other types • Calibration sensitive to wiring used to connect to sensor • Reference junction temperature compensation required
Resistance Temperature Detector (RTD)	• Nearly linear (which simplifies electronics) • Good long-term stability • Very accurate over a wide range • Interchangeable over a wide temperature range[132]	• Costs more than thermocouples or thermistors • Subject to inaccuracies from self heating • Requires lead wire resistance compensation or a transmitter at the RTD for best performance • Requires external circuit power
Thermistor	• High sensitivity • Negligible lead wire resistance errors • Good stability • Low cost • Best for limited temperature range applications	• Non-linear beyond small temperature range • May be subject to inaccuracies from self heating • Interchangeable over only a narrow temperature range • Higher tendency to drift over time • Current source required
Integrated Circuit	• Based on temperature dependence of voltage-current relationships for diodes, transistors • Linear high-level output • Low cost • Can facilitate interface with other electronics	• Smaller temperature range than thermocouples or RTDs, but adequate for most HVAC applications • Subject to inaccuracies from self heating • Power supply required • Newer technology—fewer vendors, less standardization

9.5.3.2 Pressure Sensors

Pressure sensors are accurate and reliable, and typically cost more than temperature sensors. Pressure sensors typically function properly for more than ten years, and tend to fail obviously rather than by small amounts. Typical accuracy is ±0.5% to ±1% of full scale.

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[132] In this context, interchangeable means the ability to replace one sensor with another of the same type, operating in the same environmental conditions, and get the same output (allowing for sensor error).

Pressure sensors are installed in ducts, and also—when properly outfitted—as immersion sensors in coolant, water, or refrigerant. In most cases, the sensor's environment has the greatest effect on sensor lifetime and the need for recalibration.

Table 9-17 describes the major advantages and disadvantages of various pressure sensor technologies.

Table 9-17: Types of Pressure Sensors and their Pros and Cons (based on CEC 2003)

Pressure Sensor Type	Advantages	Disadvantages
Capacitance	• Low hysteresis • High repeatability • High resolution • Fast response • Can measure low pressures	• Requires regular zeroing • Perhaps less rugged than some other technologies
Strain Gage	• High accuracy • Long-term stability • Very tolerant of overpressurization in some packages	• Strain gage bond with diaphragm may degrade
Piezoresistive	• Detects larger pressure differences than capacitive units (>5" w.c.) • Vibration tolerant	• Performance sensitive to temperature
Linear Variable Differential Transformer	• High reliability • High resolution • Lower cost for a given accuracy specification as compared to some other technologies	• Inherent nonlinearity of standard LVDT equals about 0.5% of full scale • Not as rugged, accurate as some technologies

9.5.3.3 Humidity Sensors

Humidity sensors typically cost more than temperature and pressure sensors (non-immersion), both to purchase and maintain. Polymer capacitive and polymer resistive technologies account for most of the humidity sensors used in HVAC applications. Both of these technologies experience long-term drift associated with contamination of the polymer by dust, particulates, chemicals, and chemical vapors (NBCIP 2004). In general, manufacturers recommend that humidity sensors be checked and calibrated once a year, and once every six months for sensors subjected to high temperature or humidity conditions (NBCIP 2004). Typical drift for in-duct sensors ranges from ±0.4% to ±1% absolute per year; e.g., a ±3% in-duct humidity sensor potentially becomes a ±5% sensor after two years. Consequently, humidity sensors either require frequent calibration, or end up out of calibration—either of which may prove relatively costly. Humidity sensors are installed in occupied spaces, ducts, and outdoors and are primarily used for enthalpy-based economizer control, i.e., shutdown of economizer operation when outdoor air enthalpy becomes too high. Table 9-18 summarizes the pros and cons of different humidity sensor measurement technologies.

Table 9-18: Types of Humidity Sensors and their Pros and Cons (based on CEC 2003, Fenner 2004, Adrian, 2001)

Humidity Sensor Type	Advantages	Disadvantages
Bulk Polymer Resistive	• Surface contamination does not affect accuracy • Some are interchangeable without calibration	• Accuracy varies with changes in temperature
Thin Film Capacitance	• High linearity • Low hysteresis • Good long-term stability • Wide temperature range • Some are interchangeable without calibration	• Variable accuracy with changes in temperature
Chilled Mirror Hygrometer	• Accurate • Good long-term stability	• Expensive relative to some new technologies • Requires cleaning (some self-clean)
MEMS Strain-Gauge[133]	• Resists contamination • Reduced long-term drift • Accuracy not affected by temporary water immersion • Full 0-100%RH range	• In early commercialization phase; limited commercial HVAC product available

Accuracy requirements depend on the application. Special humidity-critical applications may require ±1 or ±2% accuracy. For HVAC control applications (but not a humidity-critical application), such as in a chilled water reset strategy, an accuracy of ±3% RH may be sufficient. Less accurate (±5%) sensors can be used to monitor non-energy-critical enclosed space conditions (NBCIP 2004). In general, commercial building HVAC system humidity sensors are manufactured and sold in accuracy classes of ±5%, ±3%, ±2%, and ±1%.

Unfortunately, humidity sensor manufacturers often publish sensor accuracy data at a single temperature, which does not reveal the sensor's accuracy over its full operational temperature range. Sensor accuracy over a wide temperature range often compares unfavorably to the accuracy at a single temperature point. For example, one study evaluated the accuracy of six different humidity sensors over their intended operating range. In the range of humidities that manufacturers claimed ±3% accuracy, and for three temperatures evaluated, the sensors had the following accuracies: one sensor within ±3%, two within ±5%, two within ±7%, and one within +0/-12% (NBCIP 2004).

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[133] Based on Hygrometrix (2004a) and Adrian (2001).

9.5.4 Potential Energy Impact

Sensors do not reduce energy consumption per se, but are an enabling technology that can play a key role in saving energy in at least three ways. First, reducing sensor-related faults can reduce the additional energy consumption associated with those faults. Second, many diagnostics approaches require, or can benefit from, additional sensors and these approaches reduce energy consumption. Third, some controls approaches, such as optimal whole building control, use additional sensors.

9.5.4.1 Reducing Sensor Problems

Problems with sensors, such as inaccuracy, inability to maintain calibration, or outright failure, can cause energy waste. For example, a malfunctioning outdoor-air-temperature sensor that reads too high can cause a chiller to excessively cool circulating water; a malfunctioning supply-air-temperature sensor that reads too high can allow too-cool air to be delivered into system branch ducts, which could then require re-heating. Compounding these types of problems, malfunctioning sensors might go undetected for long periods of time, resulting in significant energy waste. Sensor accuracy is also important for maximizing the performance of building systems. Sensor inaccuracy[134] can manifest itself in many ways, including, for example, initial calibration errors, errors that vary based on whether reading nearer to zero or nearer to full scale, and long term drift errors (Hagen 1998). Sufficient inaccuracy degrades the effectiveness of control loops and can lead to subpar control decisions. Table 9-19 below describes many types of faults and flaws in sensors and their installation.

Table 9-19: Typical Faults and Flaws in Sensors (based on Hagen 1998, CEC 2003, NBCIP 2004, and Kele 2004a)

Category	Fault or Flaw Name	Description
Errors Related to Installation	lead wire resistance	lead wires have resistance and lower sensor resistance increases the impact of the lead wire resistance on the measurement; lead wire resistance depends on lead wire length, temperature, and lead wire connections; constant lead wire resistances can be calibrated out of the measurement, variable resistances can not
	electrical noise	electrical interference that alters the received signal (voltage or current) significantly
	mounting location effects	installed too close to a heating, cooling or humidifying element, installed on a vibrating or hot or cold surface
	Installation errors	not installed in the design location, wiring errors, weather housings not properly installed, condensation
	sensor-specific software coding errors	wrong lookup table data (which relates conditions to output signals)
	system software coding errors	HVAC equipment takes the wrong action based on a received signal

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[134] Manufacturers' published sensor accuracy figures often lump together several different types of inaccuracies, such as listed previously and, in addition, hysteresis, linearity, repeatability and interchangeability.

Category	Fault or Flaw Name	Description
Errors Intrinsic to the Sensor	initial calibration	errors in calibration of unit as it arrives from the manufacturer
	non-linearity	non-linear relationship between sensed variable and signal out[put, unless known and corrected for by secondary means
	Hysteresis	changes in the sensor output for the same condition when approached from a lower and then a higher condition
	repeatability	the ability of an individual sensor to provide the same output for a given condition, time after time
	interchangeability	the ability to exchange one sensor for another of the same type and obtain the same output for a given condition
	long term drift	errors caused aging effects, such as contamination of the sensing element by dirt or chemicals, or by heat
	thermal drift	a specific aging effect, caused by thermally induced degradation of electronic components over time
	self heating of resistive elements	error caused by heat from the sensor increasing the sensed temperature

Subsections 8.9 through 8.11 discuss the energy impact of controls-related faults related to sensors, in greater detail. The two categories most associated with sensor faults, “Control Component Degradation” and “Improper Controls Hardware Installation,“ have a very broad estimated annual national energy impact, i.e., from 0.005 to 0.12 quads.

9.5.4.2 Sensors to Enable Fault Detection and Diagnostics (FDD)

Many of the FDD approaches discussed in Section 9 require the installation of additional temperature and/or pressure sensors (see Table 9-20). Thus, sensors enable the technical energy savings potential of these (as well as other) FDD approaches.

Table 9-20: Sensors Required for Different FDD Applications

FDD Application	Sensors Required	Energy Savings Potential [TWh]
Dampers (Economizers)	Temperature	0.02 to 0.1
Duct Leakage	Pressure, Flow	0.15 to 0.4
RTU AFDD	Pressure, Temperature, Voltage, Current	0.024 to 0.14
Whole Buildings	Temperature, Power	0.5 to 1.8

9.5.4.3 Sensors to Enable Controls Approaches

Controls approaches studied in more detail can benefit from advances in temperature and humidity sensors (see Table 9-21). In the case of OWBCS, additional temperature sensors provide greater space temperature measurement granularity to monitor occupant comfort. This enables more flexibility in space heating and cooling provision without degrading occupant comfort.

Table 9-21: Sensors Required for Different Controls Approaches

Controls Approach	Sensors Required	Energy Savings Potential [quads]
Demand Controlled Ventilation	CO_2	0.3
Enthalpy-Based Economizer Control	Temperature and Humidity Sensors	0.1 [see below]
Optimal Whole Building Control (OWBCS)	Temperature (for comfort purposes)	0.4+

Based on a survey of smaller RTUs in California, enthalpy-based economizer control accounts for a majority (~60%) of economizer controls (Architectural Energy 2003). Temperature-based economizer control typically uses conservative dry bulb temperatures to insure that the higher levels of OA do not result in excessive humidity intake. In many climates, however, enthalpy-based economizer control could enable the economizer to operate at higher dry bulb temperature conditions when the OA has lower humidity levels, which increase the cooling provided by economizers and their annual energy savings. One analysis of the energy savings difference between OA temperature and enthalpy economizing suggest that differential enthalpy yields about a 10% reduction in cooling energy consumption (not taking into account ventilation energy consumption) for three climates, while differential temperature control saves only a couple percent (Brandemuehl and Braun 1999). Assuming that switching to an enthalpy-based system would save another 8% and applying these savings to all cooling energy for buildings with temperature-based economizers (0.2[135] quads), this suggests about an additional 0.016 quad savings. If enthalpy-based economizing were applied to the rest of commercial floorspace cooled by non-individual systems, it could realize additional savings on the order of 0.08[136] quads.

9.5.5 Performance Benefits (Non-Energy)

HVAC sensors with lower first cost and improved accuracy will benefit building owners in two primary ways. First, lower cost will tend to increase the number of sensors used in buildings for control and diagnostic approaches, increasing the market penetration of the approaches. Second, improved data quality improves the effectiveness of building controls and diagnostics. Thus, lower-cost and higher-quality sensors help to provide the benefits associated with controls and diagnostics, including improved climate control and occupant comfort and satisfaction, reduced maintenance expenditures, decreased catastrophic failures, etc. (see specific controls and diagnostics sections for non-energy benefits specific to different approaches).

9.5.6 Cost

Temperature sensors, even those with good accuracy and long lifetimes, are the least expensive of the sensors discussed in this section. Of the temperature sensors, resistance-

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[135] Based on 40% of the 0.5 quads of cooling energy for spaces served by economizers (see Section 8.5, “Dampers Not Working”).

[136] Based on 12% energy savings applied to the remaining 0.7 quads of cooling used in non-individual cooling systems. This calculation assumes that economizers would realize the same benefit in the rest of the building stock.

type sensors tend to have the lowest cost because they require the least amount of additional electronics. Humidity sensors, on the other hand, usually cost more than other sensor types, especially when lifetime costs related to calibration are included. Humidity sensors range widely in price, with higher prices typically corresponding with higher accuracy and NIST traceable calibration. Table 9-22 shows sample prices for a variety of commercially available sensors deployed in buildings. Some applications, such as factory-installed sensors used in equipment, can use simpler – and, hence – lower-cost, packaging that significantly decreases sensor cost. In addition, MEMS-based sensor have the potential to achieve much lower costs, e.g., OEM prices on the order of several dollars (or less) per sensor when produced in large volumes (see Section 9.5.8.2).

Table 9-22: Sample End-User Prices for In-Building HVAC Sensors (Multiple Vendors)

Sensor Type	Sample End-User Prices for Wired Sensor [$]	Installation Labor [$]^R
Temperature – occupied space	87-117(S), 40-130(K), 325$^{\#}$(K)	600*
Humidity – occupied space	210-660(S), 200-400(K)	
Temperature and Humidity – occupied space	270-440(K)	
Temperature – in-duct	27-180(S)	
Humidity – in-duct	125-275(N), 220-280(K)	
Temperature and Humidity – in-duct	340-360(K)	
Temperature – outdoor air	45-150(S)	600*
Humidity – outdoor air	235-290(K)	
Temperature and Humidity outdoor air	370-390(K)	
Temperature and Humidity – in-duct	210-510(S)	
Temperature – liquid immersion	40-180(S)	850*
Pressure – refrigerant	300-560(K)	
Pressure – duct differential	210-234(S), 150-200(K)	325*
Dew Point and Wet Bulb Temperature / Enthalpy – in-duct, outdoor air, room	1,325-1,425(K)	

S – Siemens online catalog (Siemens 2004), June/July 2004 (at “list price” less 40%)
N – NBCIP Product Testing Report, for ±3% accuracy sensors (NBCIP 2004)
K – Kele online catalog (Kele 2004b)
R – Based on RS Means (from Xenergy and Nexant 2002)
$^{\#}$ Transmitter matched to ice point with NIST certification (±0.14°C)
*For 50-foot cable run through conduit electric metallic tubing.

Table 9-22 reveals that, for sensors installed in buildings (e.g., as part of an EMCS), installation costs often exceed those of the sensors. All of the installation costs shown include, however, conduit electric metallic tubic installation of the wiring. This significantly increases labor costs relative to simpler wiring installations (Caffrey 2005).

Because they eliminate the need for hard-wiring between the sensors and a controller, wireless sensors have the potential to reduce the installed cost of sensor. As a result, a meaningful comparison of the costs of wireless-enabled and wired sensors needs to reflect the installed cost of both approaches to a particular application. Recently, wireless sensors have become available for buildings applications, e.,g., each of the "big three" building controls manufacturers offers wireless temperature sensors (see Table 9-23).

Table 9-23: Characteristics of Wireless Temperature Sensors Offered by the "Big Three" Building Control Manufacturers

	Honeywell	Johnson Controls	Siemens
Battery Lifetime [years]	5	3	5
Indoor Range	200-500 ft	200 ft	100 ft
Radio Frequency Mode / Communication Protocol	900MHz	900MHz	P1, 902-928MHz
Controller Types Served	A, V, U	A, V, U	A, V, U
List Price [Sensor/Receiver]	$185 / $626*	$140 - $180/ $220*	$265 / $265*
Accuracy [± F]	1	1	1

Key to Controller Types: A=AHU, E=EMCS, U=Unitary, V=VAV.
*Honeywell receiver servers up to 10 transmitters, others serve 1 transmitter
Sources: Product Literature, discussions with sales representatives.

Many options currently exist for implementing wireless sensors in buildings. A "wireless sensor" cannot operate independently—it needs to be part of a "wireless system." Each implementation and each building has unique features that impact the type and quantity of wireless system components needed, and thus the total wireless system cost. In general, a wireless data transmission system will include transmitters and receivers, and a translator to allow the wireless receiver to communicate with a control network and ultimately the building's EMCS. To help boost the strength of wireless signals, repeaters may be needed; the capabilities of the repeaters (e.g., whether they are simple repeaters or, instead, routers) depend on the type of wireless system (e.g., point-to-point, mesh). When considering the cost of a wireless system, a radio frequency survey may also need to be factored in (to determine operating ranges between transmitters and receivers on-site; see, e.g., Zebrick 2003). Figure 9-7 depicts a generic wireless data acquisition system, while Section 4.3.2.1 describes wireless systems in further detail.

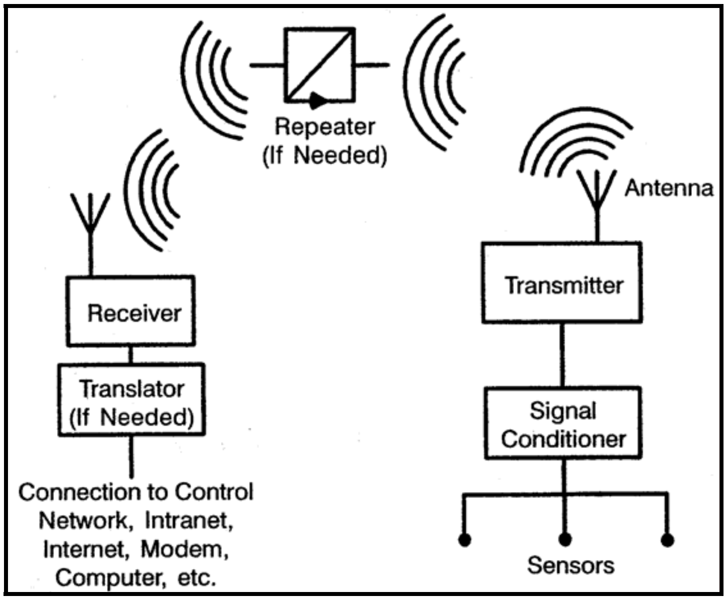

Figure 9-7: Components of a Generic Wireless Radio-Frequency Data Acquisition System (from Kintner-Meyer and Brambley 2002)

A fairly recent analysis compares two wireless systems with comparable wired systems (Kintner-Meyer 2002). The two applications studied are:

- A 30-sensor temperature sensor network (building interior sensors), and
- A monitoring system for three packaged rooftop systems.

In the first analysis, a wireless temperature sensor network with 30 temperature transmitters was installed in a three-story steel-and-concrete office building with a total floor area of about 70,000ft^2. The building is served by central cooling, a central boiler, and a central ventilation system with 100 variable-air-volume (VAV) boxes. The wireless sensors were installed to measure zone air temperatures, which were then used as inputs to a chilled-water reset algorithm. The goal of the algorithm was to reduce the building's peak demand and improve the energy efficiency of the building's centrifugal chiller under part-load conditions.

Including costs such as those of transmitters, repeaters, wiring, and labor, the investigators make a comparison of costs between the installed wireless system and a wired system that would accomplish the same sensing and communication goals (see Table 9-24). The wireless implementation includes a radio-frequency survey of the building to assist in identifying where repeaters are needed to maintain wireless signal integrity.

Table 9-24: Comparative Estimated Costs of Wired and Wireless Designs for an In-Building Temperature Sensor Network (based on Kintner-Meyer 2002)

	Cost ($)

Component	Cost ($)	
	Wired Design	Wireless Design
Sensors	1,800	3,000[137]
Wiring	4,800[138]	-----
Communication and Signal-Conditioning Hardware	-----	2,475
Labor	-----[139]	800
Total Cost	6,600	6,275
Average Cost per Sensor	220	209

In this specific implementation, the wireless system has a slightly lower estimated installed cost, although the investigators note that such a system "may range from being cost-effective to marginally cost-effective and potentially slightly more expensive than a wired system because of differences in the number of sensors and individual component costs" (Kintner-Meyer and Brambley 2002). In practice, the installed wireless communications system can handle up to 100 sensors using the base installation priced above—thus the cost of adding additional sensors equals only the incremental cost of the additional sensor and the cost to install and configure that sensor.

A more recent study compared the costs associated with installing wired and wireless systems to implement rooftop unit (RTU) diagnostics using four sensors per each of six RTUs (Katipamula and Brambley 2004; see Table 9-25). The system communicates sensor outputs from each RTU to a computer in the building. In practice, factory-installed diagnostics could have a much lower cost than either retrofit solution (see Section 9.8).

Table 9-25: Comparative Costs of Wired and Wireless Designs of a Monitoring System for Six Rooftop Units (based on Katipamula and Brambley 2004)

Component	Cost [$]	
	Wired	Wireless
Sensors	240	1,122**
Wiring	317*	-----
Communication & Signal-Conditioning Hardware	1,882	195#
Labor	2,845	1,020
Total Cost	5,786	2,337
Average Cost per Sensor	193	78
*Includes cost of ½-inch conduit. **Includes sensors, signal processing, radio transmitter #Receiver		

In this instance, the wireless solution had a much lower cost than the wired solution due to both lower labor and hardware costs. An older, similar study of four RTUs found that the

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[137] Cost is for temperature sensors with integral wireless transmitter.

[138] Includes installation labor; twisted pair wiring in a ½-inch conduit, with digital communication (RS-232) to and from the RTUs.

[139] Labor cost is included in wiring cost.

cost of the wireless system can vary substantially depending on the wireless system selected (e.g., range, data rates; Kintner-Meyer and Brambley 2002).

These cost comparisons point out that the cost-effectiveness of a wireless system is both application– and implementation–specific (i.e., the building and the wireless system). In general, the economics of wireless systems relative to wired systems becomes more favorable as the number of sensors increases. This reflects a tradeoff between higher fixed costs for wireless systems and the higher installation costs for wired systems. Wireless system costs are expected to decrease over time, and to do so at a significant rate, e.g., one market study projects that the cost of WiFi chipsets will decrease by more than 50% from 2003 to 2004 (Kintner-Meyer and Brambley 2002, Kintner-Meyer and Conant 2004). Clearly, this should increase their cost effectiveness.

Installations that are difficult to accomplish using wires present particularly attractive opportunities for wireless systems. Some examples include installation in existing buildings with special wall or ceiling treatments, such as marble or glass, or exterior installations that require trenching, such as connections to remote buildings or exterior signs. Other circumstances that may make wireless attractive include historical buildings, firewall penetration, clean room alterations, and fast-track alterations (Zebrick 2003). In cases such as these, the wired system installation costs or time requirements are sufficiently prohibitive that the wireless system is clearly preferred. Furthermore, costs of wired systems increase with distance, degree of difficulty to route wire, and code requirements. On the other hand, increased signal interference, e.g., due to large quantities of structural steel or electronic noise sources, increase wired system implementation costs (Kintner-Meyer and Brambley 2002).

9.5.7 Barriers

Sensor *installed* cost, particularly for additional sensors installed in existing buildings, poses the greatest barrier to greater use of stand-alone (i.e., not integrated with equipment) sensors in commercial buildings. The “Wireless Technologies” portions of this section (see Sections 9.5.6 and 9.5.8.1) discuss how wireless technologies may reduce the installed cost of stand-alone sensors. For sensors to be used in equipment, e.g., for RTU diagnostics, sensor cost represents the greatest barrier to their use. The “MEMS Technology” section discusses how microelectromechanical systems (MEMS) technology may reduce sensor costs.

The “Current Sensor Technology” section discusses humidity sensor-specific problems, while the “Humidity Sensors – Remedial Approaches” section reviews emerging technologies that can address these problems.

9.5.8 Enabling Technologies

Two major trends that extend beyond the bounds of the HVAC industry—wireless communications and Micro-Electronic Mechanical Systems (MEMS), have begun to transform the HVAC sensor industry. Other enabling technologies include short-term remedial approaches to address sensor calibration challenges.

9.5.8.1 Wireless Technologies

Recently, a wide variety of wireless-enabled sensor products have come to market, both within and outside of the commercial building HVAC industry. As wireless communications electronics become more power-efficient and their cost decreases further, they have the potential to have a significant impact on the building controls and systems communications infrastructure of the future. Ultimately, the success of wireless communications in commercial building HVAC systems depends on their ability to decrease the installed cost of sensors and their communications infrastructure. From an energy perspective, wireless sensors could reduce energy consumption by increasing the number of measurement points to enable FDD or enhanced building control capabilities. The realization of this potential depends on how wireless technology is applied, i.e., to increase functionality versus to reduce the installed cost of conventional building controls. Section 4.3.2.1 discusses wireless communications and sensors in greater detail.

9.5.8.2 MEMS Technologies

Technological progress related to MEMS has the potential to impact the performance and dramatically reduce the price of HVAC sensors. Conventional sensors have *end-user* prices between tens and hundreds of dollars per unit (see Table 9-22). An example from a different market segment is that from the automotive industry. Automotive sensors make extensive use of MEMS technologies (Freiburghouse 2001), as economies of scale, standardized packaging and electronics, and, in some cases, reduced accuracy requirements (relative to many HVAC applications) bring the price of automotive sensors (packaged) down to the tens of dollars per sensor, and even lower in some cases. For example, discussions with sensor manufacturers indicate that temperature sensors used for automotive HVAC systems can have an *OEM* cost of a few dollars in larger (>10,000 units) production volumes (in addition, see Kintner-Meyer and Conant 2004). At present, many conventional HVAC sensors are, however, produced in smaller volumes. In smaller lot sizes or for greater accuracy, prices would likely increase significantly.

The sensing elements themselves, especially when purchased in large quantities, are inexpensive. For example, MEMS temperature sensors can be priced at less than $0.50 per unit in high volumes (Yashar and Domanski 2004), MEMS strain-gage humidity sensor elements at $15 or less per unit (Hygrometrix 2004), and a replaceable humidity sensor element that can be plugged into a full sensor package (allowing field replacement) has an end-user price of $29.95 per unit (Precon 2004). Production volume is a very important factor in reducing price, because it enables attainment of economies of scale in machining, sub-assembling, testing, shipping and handling (Matthews 2004). Thus, to realize price benefits from economies of scale, the HVAC sensors market would need to have greater standardization in sensor components and sufficient buyer demand to drive up production volumes.

Although at least one major HVAC equipment manufacturer has begun to use MEMS sensors in some of their products, the HVAC industry has, in general, not exploited the potential benefits offered by MEMS-based sensors (Yashar and Domanski 2004). Because of the tremendous advances in MEMS-based sensors, it is likely that the amount of MEMS technology incorporated in HVAC sensors will increase over time, perhaps with concurrent price reductions. Much of the sensor cost, however, is not in the sensing element itself, but in the associated electronics and packaging that make a sensor useable in HVAC applications. Thus, equipment-integrated sensors will require low-cost MEMS sensors with improved accuracy that provide data output in formats commonly used by HVAC controllers (e.g., 4-20ma). In the case of system- or building-level controls, installation often accounts for a majority of installed sensor costs (see Table 9-22 as well as Table 6-2 from Section 6.1). As a result, MEMS-based temperature and pressure sensors will need to reduce not only sensor cost but installation cost to make an appreciable change in installed sensor costs. The low projected prices of wirless RF modules for sensors, i.e., less than \$12/unit in 2005 and \$4/unit in 2010 (Kintner-Meyer and Conant 2004), suggest that significant price reductions could occur very soon for systems with several sensors[140].

MEMS technologies also hold some promise for improved humidity sensor performance. MEMS-based strain-gage technology humidity sensors have come to market (Hygrometrix 2004) but have not found their way into widespread use in HVAC products. This MEMS strain-gage humidity sensor has a 0-100% relative humidity measuring range, and temporary immersion in water does not adversely impact its accuracy (Adrian 2001). The manufacturer anticipates that MEMS strain-based humidity sensors will exhibit less drift than the currently predominant polymer resistive and polymer capacitive humidity sensors.

9.5.8.3 Humidity Sensors – Remedial Approaches

Humidity sensors have given manufacturers reason to provide remedial calibration-maintenance methods because of the long-term drift and calibration effort posed by today's sensors. Manufacturers and sensor designers have brought different solutions to the HVAC market to address drift and calibration issues.

At least one humidity sensor manufacturer uses a hand-held portable calibrator to calibrate installed humidity sensors (GE 2004). Because sending sensors back to the factory for calibration incurs labor costs to remove and replace the sensors, on-site calibration of installed sensors can be financially attractive. On-site calibration would still incur the cost of a technician to perform the calibration, but a technician would similarly have been needed to remove and replace the sensor for factory calibration. On-site calibration would realize further cost savings because only a single device (i.e., the hand-held unit) would require factory calibration rather than each individual sensor. This hand-held device provides a single-point calibration[141]. This approach is not recommended for sensors that are exposed to a wide range of temperature and humidity, e.g., for outdoor air sensors,

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[140] Wired sensor systems have fixed costs for receivers and repeaters.

[141] That is, at one point on the sensor's temperature-humidity-voltage curve.

because sensors that operate over a wide range of temperature and humidity need to be calibrated at several points on their temperature-humidity-voltage curve (NBCIP 2004).

Another humidity sensor manufacturer offers to simplify calibration of humidity sensors by providing a relatively low-cost field replaceable/disposable sensor module (a replaceable multi-pin component; Precon 2004). Although the part has a relatively low cost, a life-cycle cost needs to consider the labor cost to replace the sensor component in contrast to the labor required to remove, replace, ship and receive a conventional sensor sent out for calibration. This specific product is not yet available in sensor products currently deployed in buildings.

At least one pressure sensor manufacturer has also addressed the need for simpler calibration (D'Acunto and Kosh 2002). This manufacturer uses a handheld calibrator and a special arrangement of pressure pathways at the sensor to allow field calibration of installed sensors.

9.5.9 Technology "Next Steps"

Several fault detection and diagnostic approaches, as well as advanced control approaches, require or can benefit from additional sensors into equipment (e.g., RTUs) or deploying additional sensors in building spaces (e.g., temperature sensors for OWBCS). In the former case, sensor cost poses the greatest barrier to increased sensor use, whereas installed cost represents the largest barrier in the latter. Ongoing industry-led development of MEMS-based sensors and wireless communications should address both issues. In particular, wireless systems for HVAC system data communication are evolving rapidly and wireless systems have come to market. They have, however, a very small market share, in large part due to a general lack of knowledge about wireless throughout the buildings industry. The following developmental next steps can help to overcome these barriers:

1. *Thorough Case Studies of Wireless Sensor Implementations*: Rigorous case studies wireless implementation will help educate building owners and controls contractors about wireless systems and decrease perceived risk. They should include:
    - Rigorous assessment of the costs and benefits;
    - Description of implementation issues encountered and how they were – or were not – overcome
    - Identification of lessons learned, and
    - Noting best practices.

    This will also help identify areas in need of further research or development.

2. *Identification, Documentation, and Dissemination of Wireless Sensor System Best Practices*: Whitepapers or other documents that provide wireless sensor system design and implementation guidance for building owners, HVAC system designers, and HVAC controls contractors in new construction and retrofit applications would

increase industry confidence in implementing systems. This could, for example, parallel an existing effort to educate people about DDC controls[142].

9.5.10 References

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[142] See www.ddc-online.org .

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9.6 Occupancy Sensor-Based Lighting Control

9.6.1 Summary

Occupancy sensor-based lighting controls determine the occupancy condition via monitoring the acoustic or thermal (infrared) characteristics of a space, and/or detecting changes in reflected ultrasonic waves generated by the sensor. Based on the sensed occupancy, the controller turns on and off lighting in the space. Occupancy sensor-based lighting control has the potential to reduce lighting energy consumption by greater than 50% in spaces with highly intermittent occupancy patterns, such as hotel rooms, bathrooms, and portions of many warehouses. On a national basis, occupancy sensors could reduce lighting energy consumption by 0.6 to 2.3 quads (the range reflects uncertainty in occupancy patterns for different spaces). Although they came to market more than twenty years ago, they have a very limited market share, i.e., only about 3% of all commercial buildings use occupancy sensor-based lighting control. High first cost, commissioning difficulties (and the resulting cost and performance issues), and false triggering pose major barriers to their greater use. The development of low-cost and low-power wireless devices that reduce the installed cost of occupancy sensors, as well as the development of more robust sensors that reduce the likelihood of false triggering, could result in greater and more effective use of occupancy sensor-based lighting control.

Table 9-26: Summary of Occupancy Sensor-Based Lighting Control

Characteristic	Result	Comments
Technology Status	Current	
Systems Impacted by Technology	All lighting	
Readily Retrofit into Existing Buildings and Systems	Yes	Wireless controls would facilitate retrofits in many cases
Relevant Primary Energy Consumption [quads]	4.2	From Navigant Consulting (2002)
National Technical Energy Savings Potential [quads]	0.6 – 2.3	See Table 9-31; up to 0.13 quads of savings from elimination of unintentional after-hours lighting (see Section 8.3)
Non-Energy Benefits	Increased lamp calendar life	
Approximate Simple Payback Period [years]	1 – 5 years	Wide range due to differences in physical space/layout and lighting watts controlled by sensor
Key Economic Barriers	Installation and commissioning costs	
Key Non-Economic Barriers	Unwanted light turn off (particularly single-technology approaches; sensor placement/commissioning also important)	
Key Enabling Technologies	Inexpensive wireless or power-line carrier controls	
Notable Developers of Technology	Watt Stopper, Sensor Switch	
Peak Demand Reduction?	Yes	
Most Promising Applications	Spaces with extended periods of intermittent occupancy, such as hotel rooms, portions of warehouses, many bathrooms, etc.	
Technology "Next Steps"	• Development of more robust occupancy sensors, i.e., with lower likelihood of false triggering • Development and deployment of wireless occupancy sensors • Sensor placement tool to evaluate expected savings in specific potential applications	

9.6.2 Background

Occupancy sensors control lighting based on space occupancy, i.e., the controls automatically switch on or off lighting according to the occupancy in that space. As an automatic lighting control strategy, occupancy sensors work best in areas with intermittent and unpredictable occupancy patterns, such as restrooms, classrooms, storage rooms, copy rooms, and closets (IAEEL 1996). According to the Lighting Research Center (2002a) and the Illuminating Engineering Society of North America (IESNA 2000), the goal of automatic shut-off controls (which include both occupancy sensors and timers) should be to turn lights off when the space is unoccupied. Manual controls should be used to turn lights on when needed. The manual on/automatic off approach reduces false triggering of occupancy sensors, i.e., sensors detect a property that suggests that a person is in a space when it is unoccupied, preventing lights from turning on when they are not needed. Some occupancy-based lighting control systems provide a local, manual override to the occupancy sensor. This is important in applications with high rates of false triggering, particularly when the lights often turn off when the space is occupied. Some facility managers, however, prefer not to provide manual overrides because they assume that people will overuse the override and nullify the occupancy sensors' energy savings.

Figure 9-8 depicts a schematic of an occupancy-based lighting controller. When the sensor detects occupancy, it sends a signal to the power pack. In turn, the power pack switches an internal relay and power flows to the controlled lights ("load").

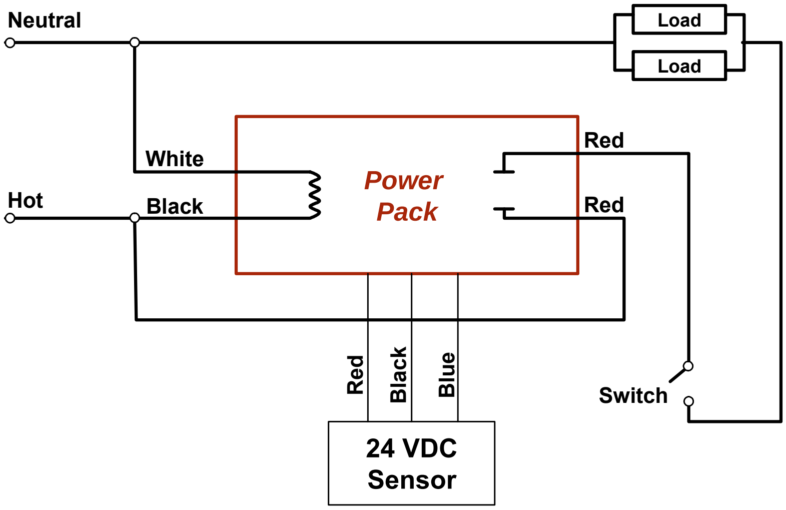

Figure 9-8: Occupancy-Based Lighting Control Schematic (based on Watt Stopper 2004)

Commercial and industrial lighting applications currently use three occupancy sensing technologies: passive infra-red (PIR), ultrasonic, and acoustic. Lighting control products can use a single sensing technology or two technologies together in "dual technology" products, notably PIR sensors with either ultrasonic or acoustic sensing. Table 9-27 highlights the advantages and disadvantages of the four different types of occupancy sensors. In all cases, proper sensor placement is a crucial component of effective occupancy sensor operation (New Buildings 2003).

Table 9-27: Occupancy Sensors and Their Advantages and Disadvantages (based on LRC 2001, LRC 2003a, and IESNA 2000)

Sensor	Advantages	Disadvantages
Passive Infrared (PIR)	• Consumes very little energy, could operate on batteries • Passive detection does not emit potentially harmful or interfering	• Have had trouble detecting small hand movements • Requires an unblocked line of sight to detect motion

Sensor	Advantages	Disadvantages
	signals • Most sensitive to movement perpendicular to direction of sensor	• Low sensitivity to movement directly towards/away from sensor • Possible false triggers: movement outside the space but visible to the sensor, sunlight falling on surfaces near windows, HVAC/machinery that heats up nearby objects
Ultrasonic	• Good spatial coverage, even with partitions and corners. Does not need direct line of sight to detect motion. • Covers larger areas than PIR because of active signal emission • More sensitive to small hand movement than PIR sensors • Most sensitive to movement towards/away from the sensor	• Emission of relatively high levels of ultrasonic has, in some cases interfered with hearing aids operating in the same frequency range* • Ultrasonic source draws up to 0.5 W, so battery operation is not practical • Possible false triggers: movement outside the space but within the sensor's range, objects blown by air currents (e.g., plants, paper, high velocity air currents from HVAC
Dual Technology: PIR & Ultrasonic	• Decreases false triggering relative to PIR or ultrasonic sensors • Covers the entire space, even with partitions and corners; direct line of sight not required to detect motion • Sensitive to motion perpendicular and parallel to direction of sensor	• Emission of relatively high levels of ultrasonic has, in some cases interfered with hearing aids operating in the same frequency range* • Ultrasonic source draws up to 0.5 W, so battery operation is not practical • More expensive than single technology systems
Dual Technology: PIR & Acoustic	• Passive detection does not emit potentially harmful or interfering signals • Decreased false triggering relative to traditional PIR sensors	• More expensive than single technology systems • Possible false trigger: acoustic sensors do not differentiate between sounds generated inside or outside the space

*Newer devices appear to overcome this problem by operating at higher frequencies (Rubinstein 2004).

PIR occupancy sensors are passive devices that are triggered by changes in the temperature pattern in their field of view, such as changes in temperature due to human bodies in motion. They are the least expensive and most commonly used type of occupancy sensor (Energy Design Resources 2000). A patterned IR lens, typically a Fresnel lens, is placed in front of a pyroelectric detector that senses infrared radiation emitted by objects at temperatures close to that of the human body. The lens receives radiation from the room in wedge-shaped areas and focuses the radiation onto the detector (see Figure 9-9). As an IR-radiating body moves in and out of each wedge, the signal strength sent to the detector changes, indicating detection of movement. The sensitivity and coverage area of a PIR sensor greatly depend on the type of lens used. A detector that comprises many narrow lens segments offers a wide field of view (e.g., for use in rooms), whereas fewer, larger lens segments produces a more narrow field of view (e.g., for use in hallways). For wall-mounted sensors, the field of view is a horizontal angle ranging up to 180 degrees and a vertical angle of up to 90 degrees. Ceiling-mounted sensors have a field of view defined by a cone that extends down and outward from the sensor (IAEEL 1996). They are best used within a 15-foot range (Energy Design Resources 2000). Figure 9-9 depicts the field of view for both wall-mounted and ceiling-mounted IR occupancy sensors.

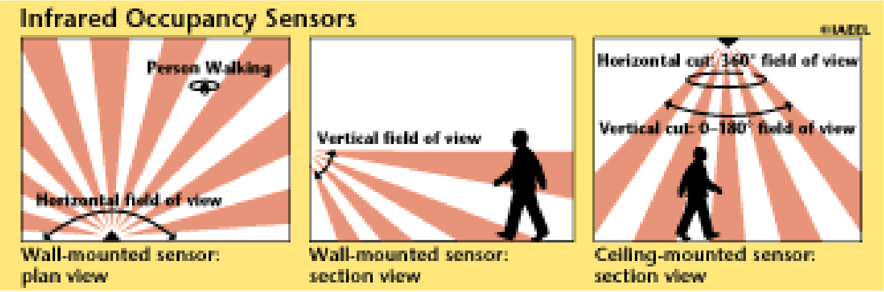

Figure 9-9: Infrared Occupancy Sensor Diagrams (from IAEEL 1996)

Ultrasonic occupancy sensors actively emit ultrasonic energy waves at high frequencies (typically 25 to 40 kHz; LRC 2001) that reflect off of objects and return to the sensor to detect motion using the Doppler effect. Ultrasonic sensors can be used by themselves or they can be deployed with PIR in dual technology sensors to reduce the occurrence of false triggers. However, most ultrasonic sensors should not be mounted on ceilings above 14 to 16 ft., as this is beyond their range (IESNA 2000).

In contrast to ultrasonic sensors, acoustic sensors use a microphone-like device to passively detect sound waves. These sensors are not used for primary detecting in commercial or industrial applications with higher ambient noise levels because the sensor will falsely trigger even when the space is unoccupied. However, they are used in dual technology sensors with PIR to reduce false triggering.

As shown in Table 9-27, false triggering can be a problem with occupancy sensors. To help reduce the chance of false triggers, occupancy sensors may have sensitivity adjustments to fine-tune operation for specific conditions. Recent advances in microprocessor technology have allowed the incorporation of sophisticated logic that automatically adjusts sensitivity, at relatively competitive prices (LRC 2001, New Buildings 2003).

The sensitivity of the occupancy sensors refers to their responsiveness to motion in the space. Most products offer an adjustable sensitivity setting that affects both the coverage area and its responsiveness to motion. Increasing the sensitivity increases the coverage area and its responsiveness to motion. Excessive sensitivity, however, may result in the sensor not turning lights off when the space is unoccupied. This is a particular problem for ultrasonic sensors (IAEEL 1996). Most occupancy sensors allow the installer to select a time delay interval (about 10 minutes is typical) for lights to remain on after the space is vacated. This helps to prevent lights from turning on and off frequently during periods with rapid changes in occupancy (which can reduce the life of fluorescent lamps; New Buildings 2003) and from turning off during periods of occupancy with little motion to be detected. Too long a time delay wastes energy and defeats the purpose of the occupancy sensor, whereas too short a time delay can cause frequent switching, which could reduce lamp life (IAEEL 1996, New Buildings 2001).

Occupancy sensors save energy by reducing the amount of time that lights remain on, thereby reducing the total electrical consumption. Occupancy sensors save energy in most situations, but save the most energy when employed in sporadically used shared spaces, such as restrooms, storage rooms, conference rooms and warehouses (LRC 2003b).

Occupancy sensors came to market more than twenty years ago. Overall, they are used in only approximately 3% of all commercial buildings. These buildings, however, account for 10% of all commercial building floor space (EIA 1999). In practice, they only serve only a portion of this floor space. Occupancy sensors are common in new construction and, according to a study conducted in California, used in up to 60% of new and retrofit commercial building construction projects (DiLouie 2004). Pacific Gas and Electric (2000) estimates that between 25% and 35% of new nonresidential buildings in California have occupancy sensors. However, only 16.7% of the spaces within these building utilize occupancy sensors, controlling 11.6% of the connected lighting load. Although occupancy sensors are a proven technology, most building owners and operators have not retrofitted their buildings with occupancy sensors (DiLouie 2004, LRC 2003b), which explains why only 3% of existing commercial buildings employ them.

9.6.3 Performance Benefits

Occupancy sensors have few non-energy benefits, which may explain their relatively low market penetration in commercial buildings. Because occupancy sensors reduce annual lamp operating hours, they have the potential to reduce lamp maintenance costs by increasing lamp calendar life. If an occupancy sensor results in frequent switching of lamps, however, it could decreases the life of fluorescent lamps (VonNeida et al. 2000, IESNA 2000), thereby reducing the benefit. Some researchers feel that occupancy sensors result in a net increase in lamp calendar life, i.e., that the benefit from decreased daily operating hours exceeds any reduction in lamp life (Pacific Gas and Electric 2000). On the other hand, properly selected modern rapid start and programmed start[143] ballasts may eliminate this problem (Rubinstein 2004).

9.6.4 Energy Savings Potential

Various sources claim occupancy sensors save between 25 and 75% of lighting energy for individual spaces (LRC 2003b, VonNeida et al. 2000, IAEEL 1996). This wide range of savings primarily reflects that the energy savings depends on type of space, occupancy patterns (frequency and duration), type of sensors/controls, time delay settings[144], behavioral patterns, and effectiveness of installation. As noted previously, sporadically-occupied spaces tend to have higher energy savings potential, such as restrooms, conference rooms, and copy rooms. In contrast, public spaces with almost continuous occupancy will garner little energy savings, such as common hallways or lobbies. The Lighting Research

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[143] Lamp cathode failure is the primary failure mechanism for fluorescent lamps. Both of these approaches preheat the cathode for a period to generate ions before striking an arc in the tube. As a result, the voltage required to strike the arc decreases relative to an instant start ballast (often used for nondimmable fluorescent lamps), which, in turn, decreases cathode wear (Rubinstein 2004).

[144] Research reported in New Buildings (2003) indicates that changing the delay setting from 5 to 20 minutes can reduce the energy savings by about 5 to 10% (absolute), depending on the space type.

Center (2003) compiled a group of 26 case studies to determine energy savings from the use of occupancy sensors. They organized the studies into broader segments based upon private versus shared spaces, and scheduled versus sporadic use, resulting in four categories (see Table 9-28).

Table 9-28: Characteristics of Spaces for Occupancy Sensor Use (from LRC 2003b)

Usage	Private Space	Shared Space
Sporadic Use	User takes “ownership” of space, such as single-person office	Examples include: public spaces, open-plan offices, restrooms, and storage rooms
Scheduled Use	N/A	Examples include classrooms

Table 9-29 shows the energy savings for each type of space as determined by the LRC. Their research clearly shows that sporadically used shared spaces have the greatest energy savings potential.

Table 9-29: Mean Percent Energy Savings from Occupancy Sensors (from LRC 2003b)

Usage	Private Space	Shared Space
Sporadic Use	25	40
Scheduled Use	N/A	30

VonNeida et al. (2000) compiled a list of industry estimates of potential energy savings for occupancy sensors, shown in Table 9-30. These data generally agree with those reported in Table 9-29.

Table 9-30: Percent Energy Savings from Occupancy Sensors (all values in %; from VonNeida et al. 2000)

Space Type	CEC	E Source	EPRI	Novitas	Watt Stopper
Private Office	25 – 50	13 – 50	30	40 – 55	15 – 70
Open Office	20 – 25	20 – 28	15	30 – 35	5 – 25
Classroom	-	40 – 46	20 – 35	30 – 40	10 – 75
Conference Room	45 – 65	22 – 65	35	45 – 65	20 – 65
Restroom	30 – 75	30 – 90	40	45 – 65	30 – 75
Warehouse	50 – 75	-	55	70 – 90	50 – 75
Storage	45 – 65	45 - 80	-	-	45 – 65

The widely varying savings show that energy savings from occupancy sensors relies heavily on the occupancy and behavioral patterns of a particular space. Table 9-31 provides the lighting energy consumption of commercial spaces and uses these values to determine the potential energy savings by space type on a national level.

Table 9-31: Percent National Technical Energy Savings Potential from Occupancy Sensors (based on VonNeida et al. 2000, Navigant 2002)

Space Type[145]	Description / Examples	Energy Consumed [TWh/yr]	Energy Savings Range [%]	Potential Energy Savings [TWh/yr]
Assembly	Auditoriums, museums, churches	12	20 – 65**	2.4 – 7.8
Restroom	Restrooms	5	30 – 75	1.5 – 3.8
Classroom	Classrooms	21	10 – 75	2.1 – 15.8
Dining	Where food is served & consumed	16	5 – 35*	0.8 – 5.6
Exit Sign	“Exit” signs	4	N/A	0
Food prep	Where food is prepared	7	5 – 35*	0.4 – 2.5
Hallway	Halls, stairs, lobbies	31	5 – 35*	1.6 – 10.9
Healthcare	Medical, nursing, labs	10	5 – 35*	0.5 – 3.5
Landscape	Exterior lit grounds	14	5 – 35*	0.7 – 4.9
Living space	Living spaces except kitchens and bathrooms	8	13 – 70***	1.0 – 5.6
Merchandise	Retail	48	5 – 35*	2.4 – 16.8
Office	Non-manufacturing workspaces	73	5 – 35*	3.7 – 25.6
Parking	Parking	11	5 – 35*	0.6 – 3.9
Shop	Manufacturing assembly and fabrication areas	17	50 – 90	8.5 – 15.3
Storage	Storage, including food	27	45 – 80	12.2 – 21.6
Signage	Illuminated signs	19	N/A	0
Sports /Recreation	Athletic/recreation areas	8	20 – 65**	1.6 – 5.2
Structure	Exterior illumination of buildings	10	5 – 35*	0.5 – 3.5
Task	Illumination for specific tasks	6	5 – 35*	0.3 – 2.1
Unknown	Unidentifiable areas	36	5 – 35*	1.8 – 12.6
Utility	Boiler rooms, electrical closets	8	13 – 70***	4.7 – 25
	TOTALS	391	N / A	48 – 190

* Open Office value from “Watt Stopper” study in Table 9-30.
** Conference Room value from from “Watt Stopper” study in Table 9-30.
*** Private Office value from from “Watt Stopper” study in Table 9-30.

Furthermore, occupancy sensors could eliminate energy consumption due to lighting operation when buildings are not occupied (see Section 8.3). This accounts for an additional 0.02 to 0.13 quads of unintentional lighting energy consumption.

9.6.5 Cost

The current list price of hard-wired wall-mounted and ceiling-mounted occupancy sensors is approximately $50 and $100, respectively (CEC 2002, PG&E 2004). Power packs[146] for ceiling-mounted sensors list at $35. Using the ceiling-mounted sensor as an example and 1,000 square feet as a basis, equipment requirements are two sensors and one power pack per 1,000ft^2, with a total cost of $235 ($0.24/ ft^2). Assuming installation requirements for simple applications are approximately 0.4 hours per sensor and 1.25 hours per power pack, installation of the basic system requires just over two hours of labor. At a burdened labor

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[145] Many space types occur in multiple *building* types.

[146] As shown in Figure 9-8, the power pack powers the occupancy sensors and activates the lighting control relay. See, for example: http://www.goodmart.com/products/428324.htm .

rate of \$60/hour, the total labor cost is \$123 per 1,000ft^2, or \$0.12/ft^2. In sum, the installed cost equals \$358 per 1,000 ft^2, or \$0.36/ ft^2 for this prototypical installation (ADL 2002). Wall-mounted occupancy sensors would cost slightly less. These values agree with another estimate for the material and installation costs of occupancy sensors between \$0.11/ft^2 and \$0.56/ft^2 based on interviews with contractors and using R.S. Means 2000 electrical cost data (Pacific Gas and Electric 2000). These costs include the cost of the occupancy sensor, wiring and commissioning and represent incremental costs, i.e., above and beyond those required for basic lighting control.

Relatively little information is available in terms of payback period for occupancy sensor-based lighting control. Manufacturer-reported case studies for office buildings in the United States estimate payback periods of 1.5 to 3 years (IAEEL 1996). A later case study at a large research campus in California showed that the installation of 8,000 occupancy sensors in offices, labs, and conference rooms reduced lighting energy consumption by 50%, giving a payback period of just over one year (Energy Design Resources 2000). An approximate calculation based on an average lighting energy consumption density of 7[147] kWh/ft^2, an installed cost range of \$0.11/ft^2 to \$0.56/ft^2, and an average electricity rate of \$0.08/kWh suggests a 1 to 5 year simple payback period for occupancy sensor systems.

9.6.6 Barriers

As mentioned previously, up to 60% of new commercial construction projects utilize occupancy sensors and up to 60% of retrofit commercial construction projects utilize occupancy sensors (DiLouie 2004). Furthermore, a recent addendum to ASHRAE 90.1-2001 that require the use of occupancy sensors in college classrooms, conference/meeting rooms, and employee lunch and break rooms (ASHRAE 2004) will increase their use in the future. Existing buildings that have occupancy sensors for some portion of the floorspace, however, account for about 10% of all commercial building floor space (EIA 1999). Three major barriers that prevent occupancy sensors from achieving greater market penetration:

1. High first cost;
2. Commissioning difficulties, and
3. False triggering.

The cost of installing occupancy sensors is a formidable barrier to their use in existing buildings, due to the difficulty of running wiring for the sensors (DiLouie 2004). Wiring is usually more difficult and expensive to replace or add in a completed building compared to wiring in a new building. In retrofit construction, the automatic controls replace existing manual controls that usually still work, in which case replacement can seem wasteful. Wireless sensors would not require additional wiring, however, and are currently under development (but would still require manual control replacement). The energy required to power the sensor represents an important consideration in wireless sensor design, since the

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[147] Based on 391TWh of site electric energy consumed by lighting in 2000 (Navigant Consulting 2002), averaged over 55 billion lit ft^2 (EIA 1999).

sensor relies on battery power. A wireless sensor design that requires frequent changing, e.g., every couple of years, would incur significant maintenance costs that drive up the life-cycle cost of the wireless sensor (ADL 2002). Even in new construction, the additional cost of installing occupancy sensors for lighting controls is not a necessary expenditure. The lighting will work without them and building owners usually prefer to reduce up-front costs rather than receiving a possible payback from the controls later.

Many building owners also have considerable uncertainty about the ultimate cost savings of occupancy sensors. The amount of energy and, therefore, money saved is very application-specific and space-dependent, as reflected in the wide range of projected savings shown in Table 9-31. It is very difficult for building owners to determine the value of installing occupancy sensors if the energy savings could range anywhere from 5% to 90%. Another cost issue is the lifetime expectancy of occupancy sensors. According to the California Public Utilities Commission (CPUC 2003), the effective useful lifetime of an occupancy sensor is approximately 8 years, as compared to 16 years for a lighting fixture. This fairly short lifetime suggest that that these sensors would require replacement twice as often as the fixtures they control.

Commissioning difficulties also have an adverse effect on the market penetration of occupancy sensors (LRC 2003a, VonNeida et al. 2000), particularly for ultrasonic sensors. The sensitivity of ultrasonic sensors needs to be carefully tailored to the application (IAEEL 1996). Some manufacturers recommend adjusting the sensitivity setting of ultrasonic sensors with the HVAC system turned both on and off to be sure that air flow won’t cause false triggers. For PIR sensors, installers sometimes need to mask a portion of the lens to restrict the sensor’s field of view. This may be to blind the sensor from activity in a hallway that can be seen through a door, e.g., a person walking past the doorway may trip the sensor and trigger the lights on (or cause them to remain on) even if the room itself is unoccupied.

False triggering occurs when the occupancy sensor incorrectly switches the lights on or off. The sensor may be too sensitive or not sensitive enough to motion or may detect motion that does not indicate space occupancy. For example, a sensor may detect motion from an adjacent area or from a plant or papers moved by air circulated by the HVAC system and improperly turn on the lights in the area with lighting controlled by the occupancy sensor. In some situations, effective sensor selection, placement, and commissioning can mitigate false positives. False negative triggers cause the lights to turn off while the room remains occupied and usually occur when an occupant(s) engage in quiet activities that require little motion, such as reading, typing, or talking on the telephone. False negative events frustrate occupants and can cause them to override the systems (if possible), defeating the energy saving purpose of the sensor. They also annoy building managers as well as occupants, since they lead to complaint calls. Unsurprisingly, one field study in California found a “great majority of people removing or over-riding the sensor due to poor functionality” (RLW Analytics 1999). Steps to reduce the frequency of false triggering include appropriate product selection, sensor placement, sensitivity level settings, and time delay adjustments (IAEEL 1996). Recent adaptive PIR-ultrasonic sensors address the latter two factors but do not obviate the need for effective sensor placement.

9.6.7 Technology “Next Steps”

Although occupancy sensor-based lighting control has been available for more than twenty years, they still serve a small portion of commercial floorspace. The following “next steps” address the barriers listed in the previous section:

1. *Development of More Robust Occupancy Sensors*: Unlike many energy-saving technologies, occupancy sensor-based lighting control does not provide appreciable non-energy benefits. Consequently, its market success suffers greatly if it inconveniences building occupants. Achieving a very low rate of false negatives is crucial for occupancy sensors to be used in a broader range of spaces than at present. Development should be closely linked with field testing of occupancy sensors that are easier to commission and decrease the likelihood of false triggering, e.g., using adaptive algorithms that tailor settings to the application. This appears, however, to be a long-standing, challenging problem due to the range of applications served by a given product.
2. *Wireless Development*: Installed system cost poses a significant barrier to occupancy sensors in many potential retrofit applications, often due to wiring expenses. The rapid development and nascent deployment of wireless technologies in buildings promises to yield low-cost, low-power, longer-life wireless occupancy sensor systems.
3. *Sensor Placement Evaluation Tool*: The payback periods for occupancy sensors have a very large range and depend on the specific occupancy patterns of a given space. This increases the financial risk of investing in occupancy sensors, which, in turn, decreases their market attractiveness. Development of a low-cost, battery-powered, removable tool that could be temporarily mounted in a space considered to evaluate occupancy patterns over a short-term period (e.g., one week) would help an owner or ESCO determine the cost-effectiveness of permanently deploying an occupancy in that space. Development of such a tool appears to be a relatively straightforward modification of existing occupancy sensors to acquire and log data.

9.6.8 References

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9.7 Optimal Whole Building Control Systems

9.7.1 Summary

Optimal Whole Building Control Systems (OWBCS) aim to autonomously control building systems and optimize building energy expenses by receiving and processing multiple inputs in real time, predicting demand for numerous potential control scenarios, and implementing the optimal building operations approach (e.g., to minimize energy costs). Information about OWBCS, particularly the energy savings achieved by the incremental improvement from an EMCS to an EMCS plus OWBCS, are sparse. Based on that limited data, it appears that an OWBCS can reduce the energy consumed by different HVAC systems by 5% to 40%, which depends on the building systems controlled by the OWBCS and the type of HVAC system(s) installed. OWBCS that incorporate knowledge of occupant behavior could also reduce energy savings by an amount similar to occupancy sensors (see Section 9.6, "Occupancy Sensor-Based Lighting Control"). On the other hand, very sophisticated and vigilant operation of building subsystems could achieve most of the OWBCS energy savings attributed to control strategies embodied in the OWBCS, excepting occupancy-based reduction of heating and cooling energy consumption. In practice, however, most building operators only use a portion of EMCS capabilities, which suggests substantial energy savings for OWBCS. OWBCS just came to market within the past couple of years and most potential customers are not familiar with the approach. Furthermore, many potential customers will not want to cede building control to an autonomous system and will perceive OWBCS as a high-risk investment. Field implementation studies that rigorously evaluate and document the benefits and costs of OWBCS implementation would help to increase the confidence of potential customers of their ability to cost-effectively reduce energy costs without compromising occupant comfort.

Table 9-32: Summary of Optimal Whole Building Control Systems

Characteristic	Result	Comments
Technology Status	Current to Advanced	*Advanced*: OWBCS incorporating individuals' whereabouts and comfort preferences *Current/New:* Intelligent-Agent Neural-Network Driven Whole Building Control Systems
Systems Impacted by Technology	HVAC, Lighting, and central refrigeration	
Readily Retrofit into Existing Buildings and Systems	Yes	May require additional sensors in some cases (wireless possible), as well as middleware to communicate with an existing EMCS
Relevant Primary Energy Consumption [quads]	9.2	HVAC, Lighting, and Large Refrigeration
National Technical Energy Savings Potential [quads]	0.5 – 1.3	Savings primarily from enhanced HVAC control, eliminating HVAC and lighting operation while building unoccupied; additional lighting energy savings possible from occupancy-based lighting control (see Section 9.6). Very sophisticated EMCS operation could realize most savings shown.
Non-Energy Benefits	• Autonomous building operation reduces staff required to operate and monitor building • Peak demand reduction, including coordinated reductions between several buildings • Potential to expand to include diagnostics functions	
Approximate Simple Payback Period [years]	Wide variation	Depends on building size, existing building systems, electric demand charges
Key Economic Barriers	Implementation cost	• Some building commissioning needed • May require middleware and additional sensors
Key Non-Economic Barriers	• Lack of knowledge about systems • Lack of confidence that OWBCS will yield promised benefits • Concerns about outside control of building systems	
Key Enabling Technologies	• Greater use of open building communications protocols, including IP-based communication (e.g., IPv6 enables many more IP addresses for building system components, improved security) • Wireless sensors (add measurement points for retrofits) • Variable speed systems increase opportunities for savings • EMCS (facilitates data acquisition)	
Notable Developers of Technology	WebGen Systems	
Peak Demand Reduction?	Yes	Peak demand reduction accounts for much of the economic justification
Most Promising Applications	A portfolio of several larger (several 100,000ft^2+) buildings with central VAV systems controlled via a sophisticated EMCS, in areas with high peak demand charges	
Technology "Next Steps"	• Field demonstrations to rigorously quantify the benefits and costs of approach to increase perceived risk of investing in OWBCS and to educate key decision makers	

9.7.2 Background

Optimal Whole Building Control Systems (OWBCS) aim to optimize building energy consumption by receiving and processing multiple inputs in real time, predicting electric demand and consumption, and subsequently controlling building systems to minimize electric bills. They differ from Energy Management and Control Systems (EMCS) in their ability to autonomously make intelligent decisions regarding building control, including predicting future behavior based on building models that consider multiple inputs. Specifically, the OWBCS develops relationships between building operating parameters and environmental conditions. OWBCS do not adhere to a pre-determined set of given parameters (e.g., rigid settings for thermostats, supply- or return-air temperature, chilled water temperature), but dynamically modifies these parameters in response to current and anticipated future operating conditions. In theory, EMCS operators can apply some of the control strategies used by an OWBCS. In practice, only a small portion of operators appear to do so (see Section 4.4). Moreover, conventional EMCS rely on the building operator to set control parameters; as a result, systems often have suboptimal control settings (see Section 8.10).

An OWBCS intelligently and autonomously manages building systems to reduce energy consumption, lower energy costs, and increase occupant comfort and safety—giving preference to one or more of these goals in accordance with multiple inputs, control system rules, and learned behavior. In addition, an ideal OWBCS could be retrofit into existing buildings, whether or not the building has an EMCS. A fully-featured OWBCS would know the building occupants' comfort preferences and habits, and information about the building and its environment that impacts its energy consumption. While fully-featured OWBCS presently do not exist as packaged products, technological progress is bringing pieces of key enabling technologies into the marketplace, and some of this technology has found its way into the building industry.

Computer scientists and others working in the areas of robotics, neural networks and intelligent agents have applied their technologies to building controls (e.g., Davidsson 2000, Sharples 1999, Mahling 2002). A consistent theme is the goal of providing a computer with autonomous reasoning and control capability similar to that of a human expert—and preferably, a team of human experts. The software constructs and modules involved in this type of behavioral modeling share many features with robotics, i.e., neural networks, intelligent agents, multi-agent systems, and embedded distributed agents.

An OWBCS amasses data in real time from multiple inputs and autonomously makes intelligent control decisions based on historical and other knowledge. Theoretically, these systems make fast, intelligent decisions 24-hours a day without human intervention using large quantities of real-time data inputs. To reduce energy consumption of buildings, current OWBCS use many of the same system and subsystem control strategies that a human operator would use, such as supply air temperature reset, chilled water temperature reset, static pressure reset, and building pre-cooling. Using models for relationships between building operations and environmental conditions, it also takes into account how building thermal mass can be used to manipulate electric load profiles and manage building electricity costs (see, for example, Braun 2003).

The following "taxonomy for technologically based intelligent buildings" (Sharples 1999) provides a general framework for discussing types of OWBCS, (see Table 9-33). The ability to learn and act on learned information separates the OWBCS from other, more rudimentary systems.

Table 9-33: Taxonomy for Technologically-Based Intelligent Buildings (based on Sharples 1999)

"Generation"	Characteristics	Example
First-Generation Intelligent Buildings	Numerous independent self-regulating subsystems; these subsystems might be relatively sophisticated.	A packaged rooftop unit with multiple cooling and heating capacities / stages controlled by a digital thermostat.
Second-Generation Intelligent Buildings	A network interconnects the subsystems, and a processor allows coordinated control of the subsystems.	An EMCS controlling a building HVAC system.
Third-Generation Intelligent Buildings	In addition to the network and processor, the system has the ability to learn, adapting its control accordingly	Optimal whole building control system (OWBCS)

Intelligent agents are key components of systems that can learn and autonomously control buildings. An agent is an autonomous intelligent control entity and each one aims to maintain understanding and control of some particular component of the total system; e.g., temperature, light, or energy consumption (Callaghan 2000).

Table 9-34 describes different types of agents based on one specific building controls implementation (Davidsson 2000).

Table 9-34: Types of Building Intelligent Agents (based on Davidsson 2000)

Type of Intelligent Agent	Role of the Agent
Personal Comfort Agent	Contains personal preferences and acts on the person's behalf to maximize, for example, that person's comfort.
Room Agent	Controls a particular room with the goal of saving as much energy as possible, it decides what values of the Environmental Parameter Agents are appropriate.
Environmental Parameter Agent	Monitors and controls a particular environmental parameter (e.g., temperature, light) in a room, and can control the devices that affect that parameter (e.g., lamps).
Badge System Agent	Keeps track of where in the building a person (i.e., their badge) is located.

In addition, intelligent agents in a specific application (such as HVAC system control) can incorporate knowledge of best practices to facilitate and increase the accuracy of their decision making. For example, these might include knowledge of well-known energy-saving practices such as supply-air temperature reset, duct pressure reset, and space pre-cooling (Mahling et al. 2004a). The intelligent agents communicate with each other and a central processor, sharing information, negotiating, and ultimately deciding what actions to take while best satisfying what often are conflicting goals, e.g. maintaining occupant comfort while minimizing energy consumption. Different OWBCS implementations may use different agent negotiation and system learning processes.

At least one commercially-available OWBCS functions at the level of a third-generation intelligent building. It uses a neural network to learn the characteristics of the building and its systems (Mahling 2002). After learning the building characteristics, the OWBCS uses the building model to explore how much many different building operating strategies can reduce integrated building energy expenditures given the current utility rate structures and current and predicted weather and building occupancy conditions. In addition, the system considers occupant comfort in the decision-making process and may add temperature sensors to ensure that the system effectively maintains acceptable conditions in different portions of a zone. The system is, however, limited in the agent types that are implemented. That is, they do not use "personalized" agents such as the personal comfort agents or badge system agents — this simply falls beyond the current state of the art for economical field deployment.

Figure 9-10 depicts a generic OWBCS implementation with a building that has an EMCS and with another building that does not have an EMCS and uses an RTU for space conditioning. The OWBCS continuously receives building operations data from each building, as well as current utility rate structure and weather information, in both cases over an internet protocol (IP) network. If the EMCS or RTU uses a controls communications protocol that the OWBCS does not "speak", the OWBCS implementation uses middleware to translate the data to and from IP to the specific communications protocols. When first installed, the OWBCS does not actively control the building systems but, instead, takes the data and uses neural network technology (see Section 4.1) to learn the relationships between whole building electricity power draw and building operational data, including weather conditions. When the neural network model variations decrease below a selected threshold, the OWBCS determines that the model is sufficiently mature to begin to control the building. Subsequently, the OWBCS continues to receive building data and also considers weather forecast (e.g., from NOAA) and utility rate data. It uses all of these inputs to calculate future building operating costs under a wide range of potential building control responses, including many classic building energy management strategies (night purge, chilled water temperature reset, supply air temperature reset, chiller staging, allowing certain space temperatures to rise, etc.). Ultimately, the OWBCS selects the strategy(s) that offer the optimal (lowest) energy costs while still satisfying basic comfort (e.g., comfort agents) requirements. This is an iterative process that repeats as building, weather, and utility data change.

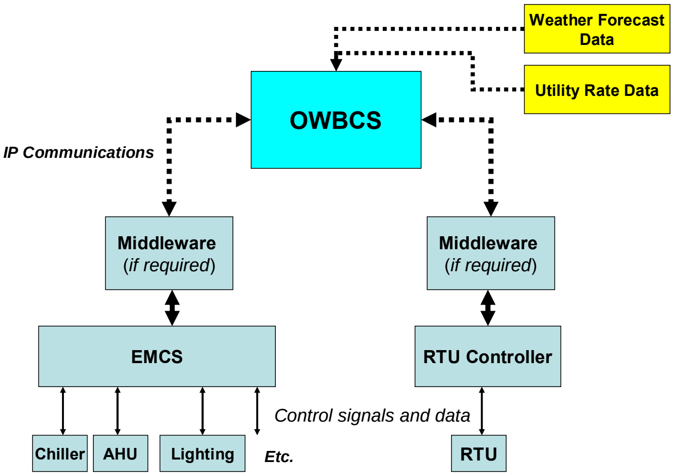

Figure 9-10: Conceptual Diagram of an Optimal Whole Building Control System

In applications where an OWBCS serves multiple buildings, it considers combinations of control actions that optimize energy costs for the entire portfolio of buildings.

This section focuses on the gains from implementing OWBCS in both buildings with a central plant and EMCS, as well as in buildings without an EMCS (typically with one or more RTUs). In the future, OWBCS functionality could extend to other building systems. Lighting systems could implement badge-based occupancy sensing and control to turn off some or all lighting in a space when the OWBCS determined that the space was unoccupied, even dynamically modifying the time delay to reflect past occupancy patterns. The energy savings would equal a portion of those achieved by occupancy sensor products (see Section 9.6). In contrast to current local sensing and control, an OWBCS implementation would likely require a more-highly-developed building infrastructure to enable both central monitoring of occupants' position and central control of space-specific lights. Automated centralized control of bi- (or multi-) level luminaires and dimming of lamps based on a photosensor in response to actual space light levels would allow reductions in lighting power draw to reduce peak electric demand. It is not clear that OWBCS would appreciably increase the energy savings potential of this approach, but the increased ability of the OWBCS to autonomously reduce energy *cost* could increase its economic attractiveness and market-achievable energy savings potential.

The OWBCS concept has also been used to manage the energy needs of a portfolio of buildings served by the same utility, thus maximizing the achievable benefits by aggregating and curtailing electric demand. The OWBCS has knowledge and control of the particular circumstances of each building in the portfolio and can rotate power demand curtailment between buildings to reduce energy cost and consumption while still maintaining occupant comfort. For example, the OWBMCS can allow the space temperature to rise in one building in the portfolio for a short period of time while maintaining temperatures in the other buildings. The OWBCS then allow the space temperature in a second building to rise while the first building resumes a higher level of cooling, and so on through all the buildings in the portfolio. In this way, the system manages the peak demand of the portfolio to avoid establishing a new peak demand high while also reducing the impact on comfort in any one building.

An OWBCS uses sensors and data input from both inside and outside of the building. These might include data and information from the energy market (i.e. tariff data), weather forecasts, building environment sensors (temperature, humidity, CO_2, light), whole building electricity meters, and building equipment sensors (e.g., chilled water temperature and supply- and return-air temperature in ducts).

Companies with OWBCS functionality have begun to come to market. Currently available systems do not have the full "theoretical" functionality, but are mostly limited to the practical and attachment-ready HVAC application. One currently available commercial product controls primarily HVAC systems and incorporates learning and predictive behaviors using intelligent agents and neural networks (Mahling et al. 2004a). The system works best in buildings that already have an EMCS – it can exchange information in multiple EMCS communication protocols – but it also can serve buildings without an EMCS, e.g., that use packaged rooftop units (RTUs). From a national energy perspective, the ability of OWBCS to serve buildings without EMCS is crucial to their ultimate national technical energy savings potential, as only about 10% of commercial buildings in 1999 had an EMCS (they comprise about 33% of floorspace EIA 1999).

9.7.3 Performance Benefits

Automated building operation reliably and continuously implements many of the building control functions that a building operator could – but often does not – perform (e.g., due to a lack of understanding of energy saving operational strategies, or rule-of-thumb operations). In effect, OWBCS replace an "expert" human operator with a software-based system, which yields several non-energy related benefits. Typically, OWBCS strives to minimize energy costs and, as noted in the previous section, achieves much of its savings by reducing peak electric demand. OWBCS also reduces the workload on facilities staff and enables them to focus on other activities, such as preventive maintenance. Alternatively, it could enable a reduction in operational staff. Furthermore, automatic operation can reduce common building controls errors related to software, hardware, and human factors. A conventional EMCS relies on settings determined by the building operator and, consequently, often have poor or suboptimal control settings. An OWBCS relies much less on human intervention, which helps to alleviate problems associated with incorrect system settings.

OWBCS also can be used to verify building energy consumption and building environmental conditions. Many EMCS have limited data collection and archiving function, and often do not measure whole building electricity consumption. In contrast, OWBCS need to track and record whole building electric power draw to minimize whole building electric cost and understand how the operating conditions of different equipment influence building power draw. This data enables OWBCS to verify electric bills and identify potential billing errors (Claridge et al. 1999). OWBCS can yield the same sort of data for other measurement points needed for the OWBCS installation (e.g., temperature sensors).

In the future, augmented OWBCS could provide ongoing commissioning to detect changes in building and equipment performance (see Section 9.10). Using the neural network or other knowledge of the building's behavior, OWBCS can compare expected and actual behavior to identify operational anomalies and drifts in performance over time. If integrated with the requisite intelligence, they could provide alarming and fault detection and diagnostics capability to identify operating problems before significant energy waste or catastrophic failure occurs. Future OWBCS could also increase occupant comfort and convenience. As they incorporate personal agents, OWBCS should be able to begin to manage building operation to address and increase the comfort of specific occupants. The OWBCS would know individuals' preferences and their whereabouts in the building, and adjust accordingly. Future building systems might be integrated at the OWBCS, e.g., occupancy sensors might provide information to the security system or indoor air quality sensors could provide information to fire detection systems to enhance smoke detection.

9.7.4 Energy Savings Potential

Few data exist from which to assess the energy savings potential of OWBCS.
One case study compared the performance of an OWBCS that controlled only HVAC parameters in a Florida office building over the course of a single month (in October). The system used neural networks to develop a model for system behavior and achieved a peak demand reduction of about 16% (kW) and electricity savings of about 10%[148] (Mahling 2004a) relative to as-usual operation via the existing EMCS. The OWBCS controlled only the HVAC system via the EMCS, and the energy savings reported are based on the total building energy usage (i.e., including lighting, hot water heating, etc.); thus it is reasonable to expect that HVAC system energy savings attributable to use of the OWBCS are well in excess of the percentages reported above. Assuming that HVAC accounted for about half of electricity consumption[149], OWBCS can reduce HVAC energy consumption by roughly 20% and its peak electric demand by about 30%. Another study compared the HVAC and lighting energy savings potential for offices using conventional control of artificial lighting (manual control of dimming ballasts), natural light levels (manual blinds), heating (proportional controller), cooling, and occupant comfort levels with automatic control using fuzzy logic combined with adaptive system models and occupancy sensing. Experimental testing over a three-month period found that the automated approach reduced total lighting and HVAC energy[150] consumption by 25% relative to conventional control (Guillemin and More 2001).

Unfortunately, these are the only installed system data found that specifically addresses the improvement from EMCS to OWBCS. An OWBCS software simulation was conducted

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[148] Reported savings were adjusted to account for number of days in the billing cycle, degree days, and "plug creep."
[149] Section 7.4 discusses the value of managing peak electricity demand.

[150] It is not clear from the article if this reflects primary energy.

using multiple intelligent agents to model the heating control of a small building in Sweden (Davidsson, 2002). This case suffered from several modeling limitations that limit the usefulness of the data, including a constant outdoor temperature (10ºC), no indoor heat loads, and negligible solar gain. Starting from a base case having all thermostats set to 22º C all the time, three other comparison simulations were run. Using a timer-based approach (thermostats set back to 16º C from 7pm to 7am), the OWBCS reduced energy consumption by 30%. A "Reactive Multi-Agent-System" approach, i.e., thermostat is set back unless the room occupant is in the building, reduced energy savings were 39% relative to the base case and 12% relative to the timer-based approach. A "Pro-active Multi-Agent-System approach, i.e., thermostats are set based on occupants' schedules obtained from their electronic diaries, yielded similar energy savings as the "Reactive Multi-Agent-System" approach. The simulations also calculated a value for occupants' comfort, intended to gauge the degree of temperature satisfaction of the building occupants; only the timer-based approach showed markedly lower satisfaction related to room temperature.

In Japan, an elaborate EMCS was installed in an existing building in Osaka Prefecture (Matsushita 2003); however, it is not clear to what extent this system could learn and make control decisions. The system integrated lighting and air-conditioning controls, monitored illumination and temperature, included automated blinds. Based on the relative costs of electricity and gas, the system controlled the building systems to achieve the least energy cost. The installation was apparently sensor-rich, being described as providing a "continuous record of …temperature distribution of each room" and, thus, should not be taken as typical. Overall, this implementation resulted in an "annual energy-saving rate" of about 27% and "conserved 38% of energy at peak hours in summer" (IPv6style 2003). A general dearth of information available about the system makes it difficult to extrapolate this result to other buildings.

Another organization has developed a product for RTUs that achieves energy savings from optimal operation and carefully monitoring of packaged HVAC systems (MPG 2004). They use a fuzzy logic controller to learn the thermal time constant of a space and adjust air conditioner compressor cycling patterns to operate more efficiently while reducing space temperature overshoot at partial loads conditions. Laboratory testing and field measurements yield about a 15 percent reduction in RTU energy consumption (MPG 2004; ITS 1998).

Overall, OWBCS appears to have a broad range of energy savings potential, which depends on the end use in question, the building systems installed (e.g., central versus packaged), building systems the OWBCS controls, the "baseline" for energy savings comparison, and the sophistication of the OWBCS (e.g., does it consider occupancy or not). Table 9-35 summarizes the approximate energy savings estimates for OWBCS by HVAC system type and end use. Central systems, notably those with VAV and variable-speed chiller plants, have higher energy savings potential than packaged RTUs with CAV because they have greater operational flexibility and can use sophisticated energy-optimization control algorithms (e.g., see Hartman 2005a). Enhanced control from OWBCS can save between 0.45 and 0.55 quads.

Table 9-35: OWBCS Energy Savings Potential Estimates from Enhanced Control, by End Use and System Type

End Use	Central	Packaged RTU	Strategies Used
Heating	10%[*‡]	10%[*‡]	Improved boiler staging, learning of boiler characteristics; reductions in temperature overshoot; occupancy-based conditioning of individual spaces
Cooling	20[*‡]% – 45[#‡]%	20%[‡**]	Central plant optimization (chiller, cooling tower, water distribution); RTU: modify compressor cycling; occupancy-based conditioning of individual spaces
Ventilation (Blowers)	0***% – 50[#]%	0%***	Duct pressure reset for VAV systems; no savings for CAV systems unless occupancy-based control of OA performed (e.g., DCV)
Sources: *Discussions with major building controls manufacturer; ** ITS (1998); *** TIAX estimate; [#]Hartman (2000), Hydeman et al. (2003); [‡]Includes approximate estimate of 5% decrease, assuming that half of commercial building floorspace can achieve a 10% occupancy-based reduction per Davidsson (2002).			

Furthermore, an OWBCS would eliminate energy waste from unintentional after-hours HVAC and lighting operation (see Section 8.3). In sum, OWBCS have a national technical energy savings potential of between 0.5 and 1.3 quads. Occupancy-based lighting control could achieve further reductions (see Section 9.6, “Occupancy Sensor-based Lighting Control”). It is important to note, however, that very sophisticated and vigilant operation of building subsystems, e.g., via an EMCS, could achieve most of the OWBCS energy savings attributed to control strategies embodied in the OWBCS, excepting the approximate 5% occupancy-based reduction of heating and cooling energy consumption. In practice, most building operators only use a portion of existing EMCS capabilities (see Section 4.4), which suggests that OWBCS still have a significant energy-saving potential.

More field implementation studies are needed to better quantify OWBCS energy savings potential for different end uses.

9.7.5 Cost

The economics of OWBCS can vary significantly with the specific application parameters (see Table 9-36).

Table 9-36: Factors that Impact the Economics of OWBCS

Factor	Comment
Building Size	Larger buildings amortize fixed costs of OWBCS over greater base
Utility Rate Structure	Higher demand charges increase attractiveness
HVAC System Design	Systems with variable speed/volume operation increase the potential range of OWBCS operation
Existing EMCS	EMCS usually increases data available, facilitates data access; OWBCS implementation may require increased EMCS capability if many measurements are added
Multiple Buildings	A portfolio of buildings enables greater flexibility in reducing electric demand while maintaining comfort
Need for Additional Sensors	Additional sensors increases implementation costs; wireless often used for additional sensors (e.g., temperature) in existing buildings
Communications Protocols	If an EMCS communicates in a protocol not accepted by the OWBCS, the implementation requires deployment of middleware

All OWBCS installations have several fixed implementation costs, such as control software and communications links. Consequently, OWBCS economic attractiveness increases with building size. HVAC system design also influences the attractiveness of OWBCS. For example, a modern building with an advanced EMCS and DDC VAV boxes with individual thermostats is a good candidate for an OWBCS. The building will need few – if any – additional sensors while maintaining a modest level of spatial detail in the sensing of building conditions. In addition, the variable frequency drive (VFD) motors on the AHU blowers provide finer system control and provide a great potential operating range for optimization to the OWBCS (Mahling 2004b)

Local utility rate structures, particularly demand charges, play a major role in determining the economic attractiveness of OWBCS. OWBCS excel at managing peak electric demand by managing different load components. In addition, many utilities offer financial incentives for peak demand reduction and OWBCS can help operators meet demand reduction requests while minimizing the impact on building occupants. If an OWBCS manages a portfolio of buildings served by the same utility, this further increases the value of OWBCS because the system can consider (and implement) a greater range of options to maximize demand reduction while minimizing the impact on occupants. Clearly, OWBCS have more attractive economics in areas with high peak demand charges.

The need for additional sensors can increase the cost to implement OWBCS. Often, EMCS do not measure whole building electricity consumption. In that case, the OWBCS can tap into the existing utility meter to measure the pulsed output and convert that signal to real-time power draw (although this can prove costly because it requires the utility's permission; Mahling 2004b). Many installations deploy additional temperature sensors to improve the OWBCS' ability minimize energy costs without compromising occupant comfort, i.e., the added sensors help to avoid uncomfortably hot or cold spots within a zone (Mahling 2004b; see Section 9.3, "HVAC Sensors," for a discussion of the installed cost of temperature sensors). In other cases, an OWBCS implementation may require improved outdoor air (OA) temperature measurements, due either to poor sensor placement or performance (Mahling et al. 2004a; Piette 2004). OA temperature is a key explanatory variable[151] in the building models developed by the OWBCS, which makes it crucial to effective OWBCS operation.

In some instances, the OWBCS cannot easily extract information from a building's EMCS because the EMCS uses a different communications protocols than those known by the OWBCS. To obtain the necessary information in such cases, the OWBCS implementation must deploy middleware to translate communications between the EMCS and OWBCS, which adds to the cost of the implementation (Mahling 2004b).

Overall, it would appear that the first cost of an OWBCS associated with an EMCS would be similar to the cost of a higher-end Whole Building Diagnostics implementation less the

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[151] That is, it has a major influence on energy consumption predictions.

cost of additional sensors, i.e., on the order of \$100,000 (see Section 9.10.5). This clearly favors deployment in larger buildings. For example, one company that sells OWBCS usually finds that their product becomes attractive in buildings that are 200,000ft^2 and larger and have an existing, well-performing EMCS (Mahling 2004b). To a large extent, the price of an OWBCS also depends on what the market will bear. Specifically, they note that their customers expect a return on investment of approximately 12 months (Mahling 2004b). A simple calculation based on national average costs for HVAC energy expenses for commercial buildings corroborates the general building size where OWBCS tend to have favorable economics[152]. On the other hand, RTUs account for more than half of commercial building HVAC energy consumption (ADL 1999, ADL 2001). Simpler RTU implementations in much smaller buildings can prove attractive if extended to several locations (e.g., several bank branches; Mahling 2004b).

9.7.6 Barriers

OWBCS face many of the barriers common to advanced controls approaches, notably a general resistance to incorporating new technology into an existing building that is perceived to work fine (Mahling 2004b; Poje 2004). The foremost goal of building operators is to avoid occupant complaints and altering building operation, let alone ceding control to software, is perceived as a risk. Moving to a new building control paradigm, such as OWBCS, is perceived as extremely risky. Building operators often believe that adding another system on top an existing EMCS increases the complexity of building operation. To feel comfortable implementing OWBCS in their building, building operators want to have real-world examples in buildings similar to theirs that clearly demonstrate that OWBCS perform reliably and achieve cost savings without compromising occupant comfort. Similarly, facility managers and corporate real estate managers want rigorous studies that clearly show the ROI in similar buildings. To date, these studies do not exist.

OWBCS vendors also indicate that many building operators are reluctant to cede control of "their" building to an outside system, for at least three reasons. First, building operators worry that an autonomously/remotely controlled building might go down if the power goes out or the communications link goes down. Even with failsafe backup operation, i.e., control reverts to the local building if the communications link fails), many building operators will likely have low confidence in an autonomously controlled system. Second, building operations staff also worry that OWBCS will make some of them redundant and may resist deployment for that reason. Third, IT staff may have security concerns about adding a software-driven control system with internet access, fearing that hackers (or worse) could exploit weaknesses in the communications system to take control of the building.

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[152] Using the rate structure described in Appendix C, a natural gas cost of \$5.50/MMBtu, and assuming that cooling and ventilation energy account for 38% and 9% of peak electric demand, respectively (Brown and Koomey 2002; Nadel et al. 2000), data from ADL (2001) yields national average annual energy costs of \$0.19/ft^2 for heating energy, \$0.38/ft^2 of cooling energy, and \$0.15/ft^2 for ventilation energy. Thus, an OWBCS that reduces heating energy by 5%, cooling energy and peak demand by 25%, and ventilation energy and peak demand by 35% reduces annual building energy consumption by about \$0.16/ft^2 due to the fact that cooling energy accounts for a high portion of peak electric demand. At that rate, an OWBCS implementation that costs \$50,000 would pay back in one year for a ~500,000ft^2 building.

The sheer diversity of EMCS communication protocols can prove a significant challenge to OWBCS implementation because it complicates extracting information from and relaying control commands to the EMCS (Mahling 2004b). The rise of open communication protocols and advances in web-enabled communications (e.g., IPv6 and IPsec; Grossetete 2004) and sensor-based servers, should reduce this issue in new buildings and, gradually, in existing buildings (see Section 4.6). New advances in sensor-based server technology and middleware will allow easier and richer communication between sensors (Corder 2004; Delin 2004).

9.7.7 Technology "Next Steps"

OWBCS presently have negligible market share. A continuing trend toward use of open building controls communications should decrease the implementation cost of OWBCS in the future. On the other hand, building owners and operators will remain skeptical of energy savings claims and ceding control of building systems to an OWBCS, respectively. Minimal data exist about the energy saving potential of OWBCS and falls short of the quality needed to give most building owners, facility managers, and building operators the confidence they require to invest in an OWBCS. Rigorous field studies of OWBCS could play a central role in establishing customer and end user confidence in OWBCS efficacy and reliability, while helping to increase potential customers' awareness of OWBCS and reduce the perceived risk of investing in OWBCS. They should thoroughly evaluate the costs and benefits of OWBCS implementation, notably: energy savings, peak demand reduction, system reliability, full accounting for implementation costs (including building staff), and evaluations of occupant comfort / complaint calls. This would include a full building commissioning prior to implementation, operation without the OWBCS for a sustained period, and subsequent OWBCS operation.

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9.8 Packaged Rooftop Unit (RTU) Fault Detection and Diagnostics

9.8.1 Summary

Packaged rooftop units (RTUs) account for more than half of commercial building HVAC energy consumption and, as discussed in section 8, appear prone to subpar operation. Common faults in RTUs include improper refrigerant charge, insufficient evaporator airflow, and fouled condensers and evaporators. Units with economizers also have a high incidence of faulty economizer function; Section 9.2, "Damper Fault Detection and Diagnostics," addresses fault detection and diagnostics (FDD) for these issues separately. Thermodynamic and non-invasive load monitoring (NILM) approaches have been proposed for RTU FDD. The thermodynamic approach uses several measurements of key refrigerant and air states to compare expected and actual vapor compression cycle performance, while NILM compares steady-state and transient electric power draw values to expected behavior. In both cases, RTU FDD could achieve appreciable energy savings over a population for RTUs while also enabling an optimization of maintenance, i.e., replacing regular maintenance with fault-based maintenance. It appears that the more mature thermodynamic approach can detect major RTU faults for an incremental price increase of less than $300 per compressor circuit if the additional sensors required for RTU FDD are installed and integrated with an existing microprocessor-based controller at the factory. With a $300 price premium to the end user, RTU diagnostics could realize a simple payback period on the order of a few years to less than a year, depending on compressor size and the magnitude of the maintenance savings. It is not clear, however, if customers in the very cost-sensitive RTU market would be willing to pay even a fraction of the $300 price premium for RTU FDD.

Table 9-37: Summary of Packaged RTU Fault Detection and Diagnostics

Characteristic	Result	Comments
Technology Status	Current/Advanced	Some existing RTUs have portions of the necessary data acquisition and processing hardware and can detect low refrigerant charge. An existing product identifies inefficient RTU operation and helps to identify problem areas (MPG 2002). Fully automated fault detection and diagnosis from measurements still in development.
Systems Impacted by Technology	All Rooftop units	Could also be applied to other commercial and residential equipment with vapor compression cycles
Readily Retrofit into Existing Buildings and Systems	Yes.	Difficult for users to access sensor readings, i.e. must be done through wireless or hardwire communication lines. Much more costly than factory integration.
Relevant Primary Energy Consumption [quads]	0.8	Primary cooling energy for packaged units (ADL 2001), including cooling-related parasitics
National Technical Energy Savings Potential [quads]	0.02 to 0.13	Range reflects the following faults: evaporator airflow obstructions, condenser fouling, and incorrect refrigerant charge. Thermostatic expansion valves can mitigate the impact of modest deviations from design charge level.
Non-Energy Benefits	Decreased maintenance costs, reduced downtime, Increased comfort.	
Approximate Simple Payback Period [years]	Less than 1 year when including maintenance savings; greater for energy only	Assumes $0.08/kWh and $300 cost premium for FDD. Various scenarios differing in EER, capacity, runtime, etc. were examined.
Key Economic Barriers	Cost to implement additional sensors	
Key Non-Economic Barriers	High uncertainty in payback period may deter investment.	Difficult to quantify benefits/savings. Energy savings and maintenance needs vary widely by climate and application. May not decrease service calls because several elements of preventive maintenance plan still must be performed manually
Key Enabling Technologies	Low cost sensors for temperature, refrigerant charge, electrical power, pressure, humidity; microprocessor-based controller	
Notable Developers of Technology	Purdue University (Braun et al.), Field Diagnostics, Honeywell, Carrier, Invisible Service Technician	
Peak Demand Reduction?	Yes	Faults impair efficient RTU operation during peak demand period.
Most Promising Applications	RTUs located in hot climates that run for most of the year, e.g. retail store in Texas.	
Technology "Next Steps"	• Rigorous field evaluation of the costs and benefits • Development of RTU AFDD for more complex RTUs • Develop low cost FDD system that focuses exclusively on faults with greater national energy impact	

9.8.2 Background

Packaged rooftop units (RTU) can develop several faults that impact their operational efficiency. Section 8 discusses three key recurring RTU faults that apply to units with cooling or heat pump heating, i.e., insufficient evaporator airflow, condenser coil fouling, and incorrect refrigerant charge[153]. These faults degrade RTU energy efficiency and cooling capacity, so it is in the building operator's interest to minimize the occurrence of these faults. Two other faults, economizer damper failure and sensor failure/degradation also can have a large impact on RTU performance and Section 8 discusses these faults in more detail. Currently, building operators call in a service technician to inspect RTUs, typically on an annual basis (Carrier 2001) or when an RTU's performance degrades to the point of noticeably affecting the building occupants' comfort, i.e., because the air-conditioner does not provide sufficient cooling for a space. RTU preventive maintenance, if performed, typically includes basic inspections to verify that mechanical and electrical systems are in good shape and function properly (Breuker et al. 2000, Julian 2001, Carrier 2001). In some cases, preventive maintenance may also include refrigeration cycle measurements to check refrigerant charge levels and heat exchanger effectiveness.

Although many RTUs have diagnostics that can detect basic functional issues, such as a blower or fan that doesn't run, these units cannot detect the aforementioned energy-related faults. RTU fault detection and diagnosis (FDD) is a system of hardware and software that automates the detection of key energy-related RTU faults and diagnoses the cause of the faults. In order to automate the fault detection process, a computer or microprocessor acquires and analyzes[154] the outputs of sensors installed on each RTU to detect and diagnose faults. Since automation allows more frequent detection of faults cost-effectively, the building operator reduces the potential for long-term suboptimal operation and catastrophic RTU damage.

Researchers (Braun 2003, Field Diagnostics Services 2002) have focused on automating detection of faults related to vapor compression cycle performance using temperature, humidity, pressure, and electrical power sensors to evaluate the thermodynamic performance the refrigeration cycle (see Table 9-38).

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[153] Braun et al. also included detection and diagnosis of compressor valve leakage and liquid line restrictions. These faults are not covered in this report.

[154] Five minute sampling period for Field Diagnostics Virtual Mechanic (ACRx 2004); one minute sampling period for Carrier IntelliSense (Carrier 2001a). The traditional manual checks are on the order of months.

Table 9-38: Sensors and Sensed Variables Used for Thermodynamic RTU Diagnostics (Braun 2003, Poje 2004)

Variable Sensed	Usually Available in RTUs w/o FDD?	
	Typical RTUs	Higher-End RTU (Carrier 2003)
Supply Air Temperature - T_{SA}	Yes	Yes
Return Air Wet Bulb Temperature (or humidity) - T_{RAwb}	No	Yes
Return Air Temperature - T_{RA}	Maybe	Yes
Ambient Air Temperature - T_{amb}	Yes	Yes; also Relative Humidity
Condenser Exhaust Air Temperature - T_{cex}	No	No
Evaporator (Refrigerant) Pressure - P_{evap}	No	Yes - Suction Pressure
Refrigerant Superheat - T_{sh}	No	No
Compressor (Refrigerant) Discharge Temperature - T_{disc}	No	No
Condensing (Refrigerant) Pressure - P_{cond}	No	Condensing Temperature
Refrigerant Subcooling - T_{sc}	No	No
RTU Power Draw	No	No

To minimize cost, researchers (Braun 2003) prefer to only add temperature sensors, usually thermistors; different developers, however, use other measurements, such as RTU power draw (Poje 2004). Figure 9-11 shows the locations of the sensors used by Braun et al. to perform thermodynamic-based FDD.

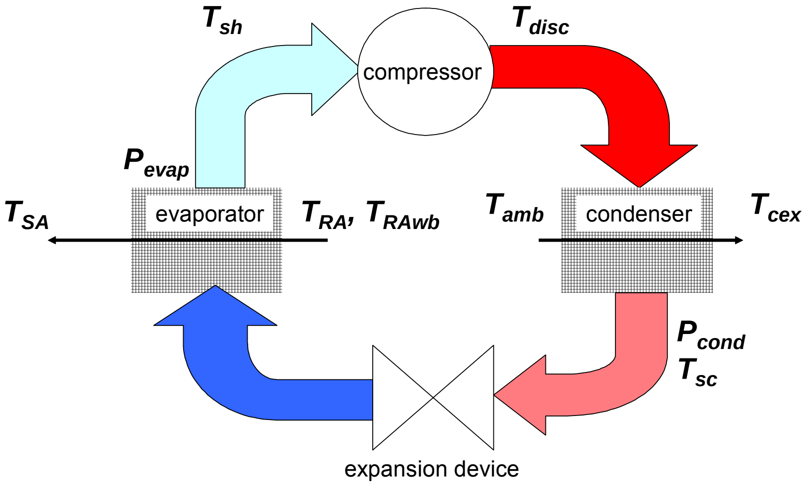

Figure 9-11: Measurements for Thermodynamic RTU Diagnostics (based on Braun 2003)

RTU FDD has three basic steps (Braun 2003):

- *Detection*: Determine that performance has deviated from expected performance, reliably and with a low false alarm rate;
- *Diagnosis*: Determine the reason why a deviation exists, i.e., a specific fault; this includes diagnosis of multiple simultaneous faults, and

- *Evaluation*: Provide information about the energy, comfort, and safety impact of the fault and recommend a course of action, e.g., immediate repair, delay repair, all systems fine, etc.

Thermodynamic-based RTU FDD algorithm uses certain parameters such as outdoor ambient temperature and indoor air temperature, as “driving conditions” for the refrigeration cycle and treats other parameters as “output states,” such as the refrigerant temperature in the evaporator coil to detect, diagnose, and evaluate faults (see Figure 9-12; a single stage cycle is shown).

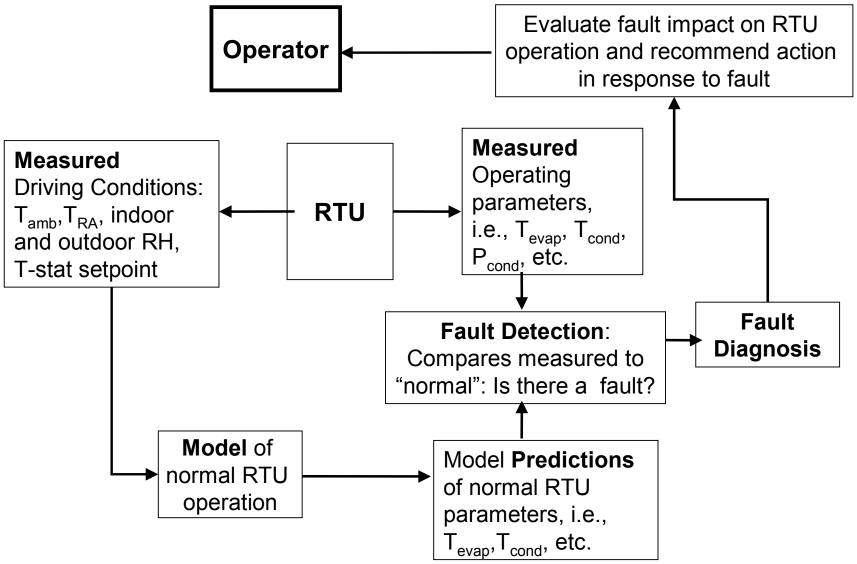

Figure 9-12: Diagram of Thermodynamic RTU AFDD Process (based on Braun 2003)

The thermodynamic AFDD system calculates expected refrigeration cycle status using the “driving conditions” based on a model (usually implemented in a computer program) that predicts performance of a properly functioning RTU. For example, the evaporator and the condenser have two-phase flow to exchange heat between the air and the refrigerant at approximately constant pressure. The AFDD system evaluates the thermodynamic properties of the refrigerant (such as R-22 or R-410A) along with temperature and pressure measurements to determine the actual state of the refrigerant entering and leaving either heat exchanger during operation. The entering and leaving states of the refrigerant can then determine the effectiveness of the heat exchanger. Coil fouling or reduced airflow will reduce the effectiveness of the evaporator. In the case of Braun (2003), low-order polynomials with a general regression neural network are used to model the “normal” refrigeration cycle. The general regression neural network aspect of the algorithm has a “learning” aspect that improves the model’s ability to predict states outside of the training data limits. This algorithm first looks at the heat exchanger faults (evaporator airflow restriction and condenser fouling) as component-level faults that can be more easily diagnosed than incorrect refrigerant charge (Braun 2003; Braun and Li 2003).

When output states vary from their expected values, this can indicate the presence of a fault. Specifically, thermodynamic AFDD takes advantage of the fact that a given fault causes output values deviate from expected values in predictable ways to diagnose faults (see Table 9-39).

Table 9-39: Correlation Between RTU Faults and the Direction of Thermodynamic Variations (based on Braun 2003)

Fault	T_{evap}	T_{sh}	T_{cond}	T_{sc}	T_{disc}	T_{cex}-T_{amb}	T_{RA}-T_{SA}
Refrigerant Leak	↓	↑	↓	↓	↑	↓	↓
Condenser Fouling	↑	↓	↑	↓	↑	↑	↓
Evaporator Fouling	↓	↓	↓	↓	↓	↓	↑

The AFDD algorithm calculates the differences between the computed normal “output states” and the measured actual “output states,” i.e., residuals. Based on the magnitudes of different residuals, the AFDD system detects whether one or more system fault(s) exists, diagnoses the type of fault(s), and determines its severity (Braun 2003, Braun and Li 2003, Field Diagnostics 2002).

Ideally, an RTU FDD system will:

- Detect faults reliably with a low false alarm rate;
- Diagnose faults (including multiple simultaneous faults), and
- Alert building operator as to next course of action, such as immediate repair, delay repair, all systems fine, etc.

Realizing these goals requires a “training” period for the RTU FDD algorithms to learn the characteristics of “normal” operation for that unit RTU under a wide range of conditions. Since each manufacturer’s RTU products behave slightly differently from the manufacturer’s other products, it is not possible to use a single performance model for all of the RTU products available. To accommodate this multitude of models, each RTU product requires its own “training” period to learn the values of the coefficients used to model different operational parameters. To maximize diagnostic accuracy, a manufacturer would carry out operational tests over the full range of potential operating conditions to establish the model coefficients. Recent research efforts in thermodynamic AFDD have tackled several important issues including (Braun 2003; Braun and Li 2003):

- *Dynamic Conditions*: Refrigeration cycle models generally assume steady-state conditions while real-world conditions only approach steady-state at certain times.

Their model overcomes this issue by evaluating the time derivatives of key parameters that change over time and performing FDD only when the derivatives fall below a threshold that indicates approximately steady-state operation;

- *Simultaneous Faults*: Identifying two or more simultaneous faults and distinguishing between their severity via simultaneous consideration of multiple residuals, and
- *Field Testing*: They performed limited field testing in RTUs located in California (Braun and Li 2003) to demonstrate the approach.

To date, a handful of FDD products have been commercialized. One product leverages the thermodynamics FDD work of Braun and other researchers to detect a similar range of RTU faults via temporary sensors. A service technician affixes a portable suite of sensors to the RTU to evaluate the unit's performance using an appropriate algorithm for that unit. The program requires the technician to input the compressor manufacturer and model into a computer program. The computer program uses the manufacturer's compressor performance data (compressor map) along with measurements of the evaporating and condensing conditions to detect faults. In addition to using readily available data, the program incorporates rule-of-thumb guidelines for refrigeration design to decide whether any faults are present. After completing the FDD evaluation, the technician usually removes the sensors (Field Diagnostics 2002). The product uses performance indices to assess the levels of several different faults (Rossi 2004). Compared to a permanent sensor installation, this approach leverages the sensor cost investment over many units while losing the capability to perform continuous FDD.

Another company sells a permanently installed FDD system for RTUs that relies on wireless communication to send the sensor data to a remote computer that controls the RTU (Poje 2004). The FDD system uses pressure, temperature, and unit (fan and compressor separately) power draw measurements to directly measure or infer numerous operating parameters, compare actual to expected performance, assess system efficiency, and determine likely sources of efficiency degradation. Subpar operating conditions identified by the system include: low supply–return temperature difference, high supply–return temperature difference, indoor air fan not working, compressor short cycling, and excessive air filter pressure drop (MPG 2002). In addition, the data and FDD analysis are readily available to the building operator on the Internet. Several of these systems are installed around the country, including a drug store chain in the northeastern US and an electronics retail store chain (MPG 2003).

An alternate, less mature approach under development uses non-invasive load monitoring (NILM) to detect faults by using current and voltage sensors to monitor the absolute, transient, and harmonic characteristics of RTU power. NILM-based FDD uses five approaches (see Table 9-40). For example, a *change of mean* approach compares the measured power draw to the expected power draw under given operating conditions. Presumably, NILM-based FDD would also require temperature measurements to establish operating conditions and the resulting expected current, voltage, and power characteristics.

Table 9-40: Approaches Used for NILM-based FDD (based on Armstrong et al. 2004)

Approach	Variable(s) Analyzed	Potential Faults Detected
Current and Voltage Imbalance	Ratio of current and voltage	• Loss of motor phase
Change of Mean	Mean power (reactive or apparent) draw	• Improper refrigerant charge • Fouled condenser coil
Start Transients	Startup power signal (time series)	• Locked rotor • Slow starting motor • Liquid ingestion (transient during operation)
Event Sequence	Timing and sequence of motor state in response to control action	• Short cycling • Motor failure to start • Incorrect control sequence
Amplitude Spectrum	Amplitude of selected frequency bands at steady state conditions	• Fan rotor imbalance

Preliminary laboratory testing has revealed that NILM-based FDD can yield distinctive signatures for several faults under at least one operating condition (Armstrong et al. 2004). It is unclear, however, if NILM-based FDD can reliably detect the same range of faults as thermodynamic-based FDD.

Because the costs of FDD are relatively fixed, chillers with their large capital investment and greater potential energy savings often provide information that can be used to detect and diagnose faults, e.g., refrigerant charge levels, refrigerant and cooling water temperatures to evaluate condenser performance. More recently, some larger RTUs also have limited diagnostics that go beyond basic functionality (Carrier 2003). For example, a major RTU manufacturer incorporates sensors and logic capable of detecting low refrigerant charge and sensor status in some larger units (20 to 60 tons; Carrier 2003). A few organizations have focused on RTU economizer faults instead of the faults covered in this section; Section 9.2 addresses those diagnostics.

9.8.3 Performance Benefits

In addition to reducing energy consumption, FDD can detect problems before they lead to more costly failures, such as compressor failure. Not only would this avoid an expensive repair, it would also avoid the downtime associated with the repair (e.g., at least several hours), during which the space could become uncomfortably warm during periods of hot weather. RTU FDD also gives building owners more control over inspections and service calls. Early detection of RTU problems allows owners to schedule service during less-busy times before the fault develops into a serious problem. In some instances, maintenance may be overscheduled, so reducing preventive maintenance calls will save the building owner money and time. On the other hand, RTU FDD will probably not eliminate basic service calls because regular maintenance includes several activities not related to FDD (Breuker 2000, Julian 2001, Carrier 2001). Finally, RTU FDD enables building owners to verify the effectiveness of repairs, i.e., that the work was performed and remedied the problem(s).

Improved RTU maintenance can also enhance building occupant comfort, which is the primary goal of building operators. Similarly, superior maintenance helps to prevent supbar

RTU operation that can decrease occupant comfort and, potentially, also decrease employee productivity and customer sales[155]. For example, an RTU with lower cooling capacity due to a fault operates (effectively) as a smaller air-conditioning unit that cannot effectively cool the building on very hot days. .

9.8.4 Energy Savings Potential

Assuming that RTU FDD remedies the key faults of insufficient evaporator airflow, condenser coil fouling, and incorrect refrigerant charge, it could reduce national primary energy consumption by 0.025 to 0.14 quads (see Section 8). As with any diagnostic approach, this assumes that the end user fixes the faults after diagnosis. In practice, this may not always occur.

The energy savings potential for a specific RTU FDD application can vary greatly because it depends on the cooling energy consumed by the unit, whether or not the unit has a given fault, and the severity of faults. Clearly, FDD will save more energy for RTUs that have higher fault incidence (due to lack of maintenance or a challenging environment) or longer operating hours (particularly to provide cooling).

9.8.5 Cost

For thermodynamic-based RTU AFDD, the sensors and the communication links between the sensor data and the processor/computer account for most of the cost in new units. Two basic approaches exist to implement thermodynamic-based RTU AFDD, centralized and on-board (see Table 9-41).

Table 9-41: Characteristics of Centralized and On-Board RTU AFDD Implementations

AFDD Approach	Description	Pros and Cons
Central	• Uses wired or wireless communication of sensor outputs to central CPU • Fault detection and diagnostics performed at central CPU	Pros: Close to real-time communication of specific faults to building operator; could enable automatic notification of maintenance or repair personnel Cons: RTUs not controlled by an EMCS or device with flexible user interface require new communications infrastructure, increasing cost
On-Board	• CPU-based RTU controller • Controller communicates signal indicating a generic fault to thermostat (with fault indicator) • Personnel access RTU to determine precise fault	Pros: Leverages existing communications infrastructure for many RTUs, i.e., signal to thermostat; Low cost Cons: Requires in-person examination of RTU to determine precise nature of fault[156]; building personnel must notice thermostat indicator

The cost of installing communications infrastructure makes the centralized case appreciably more expensive than the on-board case. For example, Katipamula and Brambley (2004) estimate an installed (end-user) cost of about $950 and almost $400 *per RTU* for a

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[155] Honeywell (2004): “sales decline 15% when customers are uncomfortable…employees are 2 to 10% less productive.”

[156] For the Central approach, maintenance staff may check the RTU to confirm a fault as a first step, i.e., prior to calling HVAC technicians.

diagnostic system that monitors five measurement points on each of six RTUs via wired and wireless communications, respectively. Another study estimates an installed (end-user) cost of approximately $300 *per sensor* installed for RTU diagnostics (Kintner-Meyer and Brambley 2002; see Section 9.6.4). In both cases, the communications infrastructure costs significantly more than the sensors. One company that has implemented RTU FDD noted that they charge approximately $3,500[157] per RTU for hardware, installation, and operations fees (Poje 2004).

In contrast, the on-board system leverages the existing communication system to a thermostat[158] to alert building operators of a fault, i.e., the RTU controller would relay the fault to the thermostat and the operator would consult the controller to determine the nature of the fault. Although thermostats with this capability appear to have a small market share, they should have a significantly smaller incremental cost than establishing a full-blown communications link. Ultimately, sensor costs provide a feel for the minimum cost of on-board RTU FDD in new units (see Table 9-42). These OEM prices are much less than the sensor prices presented for building sensors installed in buildings. This reflects the different packaging (installation, environment, outputs) requirements and purchasing volumes for building sensors (see Section 9.5). Installation (i.e., not including the cost of the sensor) of all the temperature and pressure sensors listed below would add a few dollars to the manufacturer's cost, with labor and wiring costs accounting for most of the additional cost (TIAX Manufacturing Cost Estimate).

Table 9-42: RTU Diagnostics Sensors for Thermodynamics-Based AFDD and Their Approximate Costs

Variable Sensed	Sensor Available in Typical Unit?	Approximate OEM Sensor Costs[159]
Supply Air Temperature - T_{SA}	Yes	$0
Return Air Wet Bulb Temperature - T_{RAwb}	No	~$15 (humidity)
Return Air Temperature - T_{RA}	Maybe	<$5
Ambient Air Temperature - T_{amb}	Yes	$0
Condenser Exhaust Air Temperature - T_{cex}	No	<$5
Evaporator (Refrigerant) Pressure - P_{evap}	No	~$20
Refrigerant Superheat - T_{sh}	No	<$5
Compressor (Refrigerant) Discharge Temperature - T_{disc}	No	<$5
Condensing (Refrigerant) Pressure - P_{cond}	No	~$20
Refrigerant Subcooling - T_{sc}	No	<$5

The total incremental OEM cost of sensors needed to implement thermodynamics-based RTU AFDD of less than $80. In addition, the system requires a microprocessor[160] with

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[157] When deployed in a region with very high electric demand charges, the developers claim a return on investment of about 33% from energy savings alone (Poje 2004). In practice, much of cost savings likely accrue from application of selected control strategies employed to reduce unit peak demand and energy consumption (decreasing unit cycling).

[158] For example, the Honeywell T8511M.

[159] OEM prices estimated for purchasing volumes on the order of 10,000 units, based on discussions with multiple sensor manufacturers. In general, prices are quite sensitive to sales volumes

[160] Some new RTUs use microprocessor-based controllers, particularly larger units (which often have VAV).

greater data acquisition capability than those used in existing RTUs, which would moderately increase the $80 cost premium (Li 2004). An alternate RTU AFDD approach using nine temperature sensors would have an incremental OEM cost well below $50. For comparison sake, Braun and Li (2003) assume that incorporating FDD into an RTU would increase the cost of an RTU to the end user by $300 for ten sensors. Both estimates are quite low when compared to cost estimates for retrofit installations of hard-wired or wireless sensors. None of these estimates include development costs for the AFDD system.

Developers of NILM-based FDD state that a three-phase RTU would require two current and two voltage sensors. In addition, implementation in each RTU would require significant data acquisition (to acquire system voltages and currents) and processing capability, such as provided by a "PC-on-a-chip" combined with the voltage and current transducers (Armstrong et al. 2004). A key NILM developer indicates that the "PC-on-a-chip[161]" would dominate the cost and that the entire package would have an approximate OEM cost of $200 (Armstrong 2004). In most cases, the "PC-on-a-chip" would replace electronic controls, that cost (OEM) on the order of tens of dollars (TIAX estimate). Continuing advances in microelectronics and computing suggest that these costs will continue to decrease in the future.

In addition to reducing RTU energy consumption, diagnostics have the potential to reduce RTU maintenance costs relative to scheduled preventive maintenance in several ways (Li and Braun 2004), including:

- Reduction or elimination of major (e.g., compressor) faults;
- Maintenance performed as needed;
- Coordination of maintenance activities for sites with multiple RTUs (e.g., perform "regular" maintenance when called in for a fault), and
- Reduced time to service faults (from information provided by diagnostic system versus an emergency call).

Calculations based on their methodology and many of their assumptions suggest that RTU AFDD can reduce annual maintenance costs by roughly $70/ton for a site with four (4) RTUs. Coordination of maintenance activities for several RTUs accounts for much of the benefit; a similar analysis for a site with a single RTU suggests more moderate savings, on the order of $25/ton/year.

Figure 9-13 compares the simple payback period[162] for thermodynamic AFDD as a function of unit size (assuming a single compressor).

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[161] A "PC-on-a-chip" can run various (simpler) operating systems, has a microprocessor with less computing power than a PC (but sufficient power for many applications, e.g., consumer electronics), and has input-output capability.

[162] This figure reflects the following assumptions: $300 end-user cost premium, $0.08/kWh for electricity, 1,250 full-load equivalent cooling hours of operation per year (compressors account for an average of 70% of unit energy consumption during those hours), and a unit EER of 10.

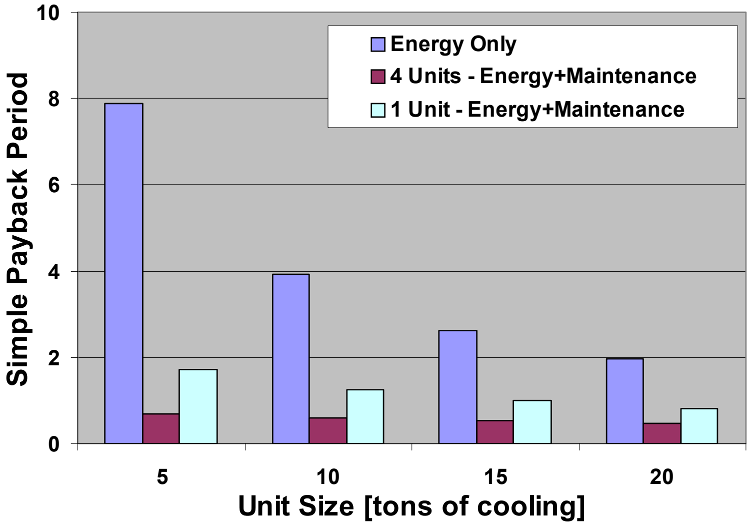

Figure 9-13: Estimated Simple Payback Periods for Thermodynamic RTU AFDD

Figure 9-13 clearly shows that RTU diagnostics provide greater economic benefits from maintenance savings than from energy savings. In addition, RTU AFDD has more favorable costs as unit size increases RTUs. Additional calculations suggest that the number of compressors per unit does not have a large impact on SPP values that include maintenance-related savings, i.e., the increased cost to implement AFDD for each vapor compression cycle is offset by additional maintenance savings. The number of compressors, on the other hand, has an appreciable impact on the SPP of RTU FDD for a given unit size if the calculation only considers energy savings. This reflects that the costs to implement RTU AFDD scale (roughly[163]) linearly with the number of compressors, i.e., the cost of sensors for a 10-ton RTU with two 5-ton compressors is approximately twice that for a unit with a single 10-ton compressor.

In addition, energy savings depends heavily on cooling energy consumption, so RTUs that have light cooling usage, e.g., those located in heating-dominated climates, will usually have longer payback periods. The increase in payback periods will be greatest in payback assessments that only consider energy savings.

9.8.6 Barriers

Higher first cost and a lack of thoroughly documented field evaluations impede deployment of factory-installed thermodynamic-based RTU FDD. At first glance, a $300 – or potentially $100 – cost premium to the end user for a viable combination of sensors appears to be relatively small compared to the installed cost of the RTU ($750 to $1,000 per ton installed; Braun and Li 2003). The unitary market, however, is very sensitive to price and

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[163] The linearity of this function depends on the relative cost of the senosrs, which is fixed per compressor, and that of costs shared for the entire unit (potentially the microprocessor).

most manufactures and purchasers of RTUs will likely have a difficult time accepting even small cost premiums. Furthermore, RTU diagnostics will only reduce the operating expenditures for units that actually have faults. Thus, RTU diagnostics cannot guarantee energy savings for a given unit and will realize little energy cost savings benefits for a portion of units. Ultimately, it should also integrate damper FDD (see Section 9.2), as RTU manufacturers will prefer a single, integrated FDD suite instead of multiple FDD packages.

RTU AFDD also faces technical barriers for more complex RTUs. To date, RTU AFDD has only been demonstrated for a unit with one single-capacity compressor. Many RTUs have multiple compressors and separate AFDD sensors for each circuit should be feasible if the circuits do not interlace with each other. On the other hand, systems with more features, such as variable-capacity compressors, variable-air-volume blowers, staged or variable-flow condenser fans, hot liquid reheat, etc., will increase the complexity and difficulty of implementing RTU AFDD.

NILM-based RTU AFDD is less mature than thermodynamic-based AFDD and, consequently, requires greater developmental progress to reach the market. Very limited, preliminary test results for a single unit suggest that NILM can identify electric power signatures for several key faults (Armstrong et al. 2004). Future development is needed to address several practical issues with NILM, including:

- Signature development under different test conditions;
- Effective detection of multiple faults;
- FDD for units with multiple refrigeration circuits and/or VAV, and
- Development of appropriate thresholds for AFDD.

In addition, NILM-based RTU AFDD currently appears to cost significantly more than the thermodynamic variant. The cost of the solid state electronics and processing capabilities at the heart of NILM should continue to decrease rapidly in the future and, perhaps, make it cost competitive with thermodynamic AFDD.

To enhance the commercialization prospects of all approaches, AFDD computer software needs to detect faults reliably, i.e., too high a false alarm rate could increase the cost of servicing and managing the products. In addition, the software must effectively diagnose faults (including multiple simultaneous faults), and alert building operators to the fault. Ideally, the FDD tool would also provide recommendations as for the next course of action, e.g., immediate repair, delay repair, all systems fine, etc., based on their cost-effectiveness. In all cases, developers will need to build confidence among consumers that automated FDD is effective and easy-to-use before widespread commercialization begins.

These factors suggest two potential initial niches for RTU diagnostics. First, manufacturers who market their products to larger customers who take into account total cost-of-ownership when purchasing RTUs should have a greater interest in diagnostics. On the other hand, these customers may pay more attention to unit maintenance than other users, which would tend to decrease the rate of faults and, hence, the energy savings potential of diagnostics. Second, the relatively fixed cost of RTU diagnostics makes deployment in RTUs with larger compressors more attractive, because the diagnostics realize a greater cost savings benefit for the same investment in those units.

9.8.7 Technology "Next Steps"

Thermodynamic RTU AFDD has made significant progress through research and development efforts, as well as limited field testing. It, however, still faces major cost barriers to commercialization, most notably the strong reluctance of many customers (and, hence, manufacturers) to incur any cost premium for RTUs and the cost to manufacturers to develop RTU AFDD algorithms for their equipment. Consequently, development efforts need to focus on minimizing the cost impact to manufacturers of both RTU AFDD development and implementation. In addition, field studies to demonstrate its effectiveness would help manufacturers to build a more compelling business case and overcome customer concerns about new (and, from their perspective, unproven) technologies. Four "next" steps would help RTU FDD make the transition from a developmental effort to a feature of actual RTU products, including:

1. *Development of a Cost-Optimized Thermodynamic FDD System*: A system that detects only the most common and energy-intensive faults may not require all of the sensors used in a more complete FDD system while offering a superior energy cost savings to FDD cost ratio. Although this would have a *lower theoretical* energy savings potential than a comprehensive FDD system, the improved cost structure would increase the market penetration of FDD systems and result in *higher actual* energy savings. Along these lines, thermodynamic FDD should also diagnose key damper faults (see Section 9.2). The California Energy Commission has recently funded a project to develop a commercialized RTU diagnostics product[164] within two years, with Honeywell as the commercialization partner.
2. *Extension to More Complex Units*: Thermodynamic RTU FDD has been demonstrated for basic units with one single-capacity compressor. To reach the bulk of the market, it requires further development for units with multiple refrigeration circuits, as these units appear to account for a majority of RTU energy consumption. Further development is needed to assess its viability for units with energy-efficient features that complicate AFDD, such as VAV and variable-capacity compressors. The multiple potential configurations and features suggest that this will require a substantial research effort beyond current efforts.
3. *Rigorous Field Tests*: Potential customers have shown very little interest in adding FDD capability to RTUs and are generally wary about investing in unproven technology. Field tests that thoroughly evaluate and document the costs and benefits of RTU FDD, particularly energy and maintenance savings,

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[164] See http://www.archenergy.com/pier-fdd/rtu_diagnostics/rtu_diagnostics.htm for additional information.

would provide better data to help end users make informed decisions about investing in RTU FDD.

4. *Further Development of NILM-based AFDD*: Although NILM-based RTU AFDD appears to cost significantly more than thermodynamic AFDD, continued reductions in the cost of the necessary electronics and processing capabilities could increase its future cost competitiveness. Relative to the thermodynamic approach, NILM may offer a more promising approach to AFDD for more complex units. It has shown promise in very limited testing, but requires much more development to address several issues. Specifically, NILM-based AFDD needs to demonstrate that it can: yield distinctive and discernable fault signature for a wide range of operating conditions, detect faults when multiple faults occur, and detect and diagnose faults for units with multiple refrigeration circuits. In addition, appropriate thresholds for AFDD must be developed.

9.8.8 References

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9.9 Photosensor-based Lighting Control

9.9.1 Summary

Photosensor-based lighting control varies the quantity of electric lighting output in response to the sensed quantity of visible light (both natural and artificial) to achieve a minimum level of light in a space. It can be used to for both daylighting and lumen maintenance. Daylighting reduces electric lighting output in response to the amount of available daylight in the space, while lumen maintenance reduces the illumination of lighting systems to design levels. A wide range of estimates exist for the energy saving potential of photosensor-based lighting control. Daylighting, in particular, has large ranges that reflect the amount of daylight available to the space and the nature of the daylight. Overall, photosensor-based lighting control has a national energy savings range of 20% to 40% of lighting energy use within applicable buildings, or 0.4 to 0.8 quads of primary energy. In practice, however, daylight-linked systems often do not achieve the anticipated energy savings due to improperly installed or commissioned systems, use of darker indoor materials that reduce light reflections, and occupant overrides of systems. Currently, they do not serve a large portion of commercial floorspace due to the high cost of the dimming ballast, the complexity of proper photosensor system installation and commissioning, a lack of evidence that the technology routinely works and provides the expected energy benefits, and the need to consider daylighting during building design for effective implementation. The development of lower-cost and efficacious dimming ballasts and clear daylighting design and implementation guidance to improve installation can enhance the cost-effectiveness and, therefore, market penetration of photosensor-based lighting control.

Table 9-43: Summary of Photosensor-based Lighting Control

Characteristic	Result	Comments
Technology Status	Current	Less than 1% of commercial floorspace likely served by systems with continuous dimming
Systems Impacted by Technology	All lighting	
Readily Retrofit into Existing Buildings and Systems	Depends	Building and space architecture plays a key role in the suitability of daylighting
Relevant Primary Energy Consumption [quads]	4.2	Navigant Consulting (2002)
National Technical Energy Savings Potential [quads]	0.4 to 0.8	Greater use of skylights would increase energy savings potential, both on a percentage (for a space) and quad basis; additional cooling energy savings possible
Non-Energy Benefits	Increased lamp calendar life for daylighting systems in many applications; decreases lamp replacement costs	California's Title 24 building code provides a credit for automatic lighting controls in daylit zones that effectively reduces the calculated installed lighting in that zone. This reduces the effective lighting wattage for the whole building (New Buildings 2003).
Approximate Simple Payback Period [years]	10+ years	Due to high dimming ballast costs and system commissioning costs
Key Economic Barriers	High cost of dimming ballasts, complex installation and commissioning often time-intensive	
Key Non-Economic Barriers	High uncertainty of payback (quite application-specific), daylighting requires integration with building architecture (e.g., skylights, building orientation, fenestration, window treatments)	
Key Enabling Technologies	Wireless communications between photosensor and dimming ballasts to increase installation ease, notably in retrofit installations where one photosensor controls several ballasts	
Notable Developers of Technology	Watt Stopper, Sensor Switch, Lighting Research Center (RPI), Lawrence Berkeley National Laboratory	
Peak Demand Reduction?	Yes	Lighting power reductions often correlate strongly with peak electricity demand
Most Promising Applications	Buildings that admit significant quantities of light to most areas of the building, with even light distributions; warehouses with skylights have promising economics but typically use stepped (versus continuous) lighting control because of lower cost and light quality requirements	
Technology "Next Steps"	• Improved daylight simulation and energy impact software tools • Field demonstration and market promotion of products to expedite photosensor commissioning • Daylighting design and implementation guidance Increase production volumes of dimming ballasts to reduce their cost (e.g., via market promotion activities) • Increase production volumes of dimming ballasts to reduce their cost (e.g., via market promotion activities)	

9.9.2 Background

Photosensors detect the amount of visible light (both natural and artificial) in a space. The photosensor sends a variable output signal (usually proportional to the detected light level) to the controller that continuously adjusts the electric lighting output to dim the artificial lighting when necessary, either independently or through an EMCS, to automatically maintain the desired lighting level. The photosensors discussed in this section are for dimming lighting in commercial applications for energy efficiency purposes rather than for architectural dimming for aesthetic or multi-media purposes. Bi- or multi-level switching lighting controls that adjust lighting output of either individual ballasts (multistep ballasts) or individual lamps in discrete increments also exist. Although frequent discrete changes in light output levels can distract occupants and limits the use of multi-level switching in many locations and applications, they can provide acceptable lower-cost daylighting control in spaces with transient occupancy (won't notice changing light output as much), where non-critical tasks are performed (light output changes less distracting), and that consistently receive high levels of daylight throughout the day (few changes in light output; New Buildings 2003). The discrete nature of multi-level switching also decreases its energy-saving benefit, particularly in lumen maintenance applications. Consequently, this section focuses on dimming-based systems.

The light-sensing element of a photosensor can either be a photodiode, a phototransistor, or a photo-resistive cell (LRC 2001). Dimming systems vary the lamp output in response to the varying photosensor irradiance (see Figure 9-14 for an example of a fluorescent lamp-based system). When the photosensor detects an increase in illuminance, the controller (typically integrated with the photosensor) sends a signal to the dimming ballast which, in turn, decreases the power flowing to the lamps. Similarly, when the photosensor detects a decrease in illuminance, the controller sends a signal to the dimming ballast to increase light levels. Dimming systems can be applied to fluorescent, incandescent, and high-intensity discharge lamps. This section focuses on fluorescent lamps because they account for about 55% of commercial sector lighting energy consumption (Navigant Consulting 2002). As shown in Figure 9-15, fluorescent lamp-ballast efficacy decreases with dimming level. Standby power draw levels of up to 6W[165] (New Buildings 2003) result in more precipitous decreases in efficacy at low light levels.

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[165] For a two-lamp ballast.

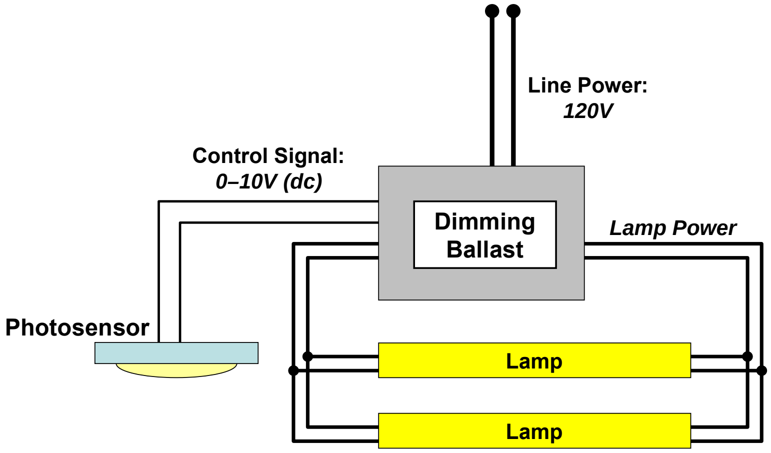

Figure 9-14: Control Circuit for Photosensor-based Lighting Control

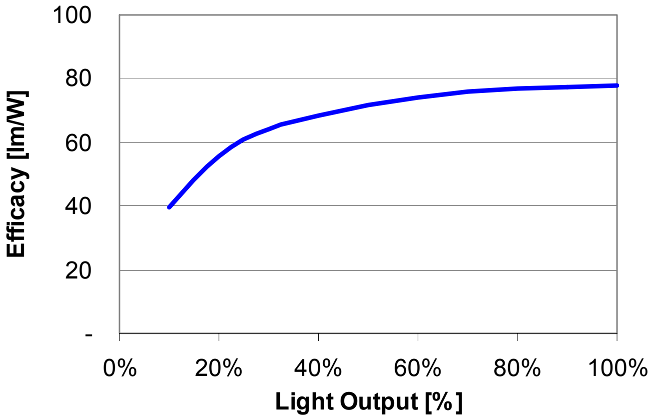

Figure 9-15: Illustrative Variation with Fluorescent Lamp Efficacy with Lamp Output (based on New Buildings 2003)

Photosensor-based control is an integral part of two energy management strategies: daylighting and lumen maintenance. In both strategies, photosensor-based lighting control continuously adjusts light output throughout the day such that the lamps output only the required quantity of light (see Figure 9-16).

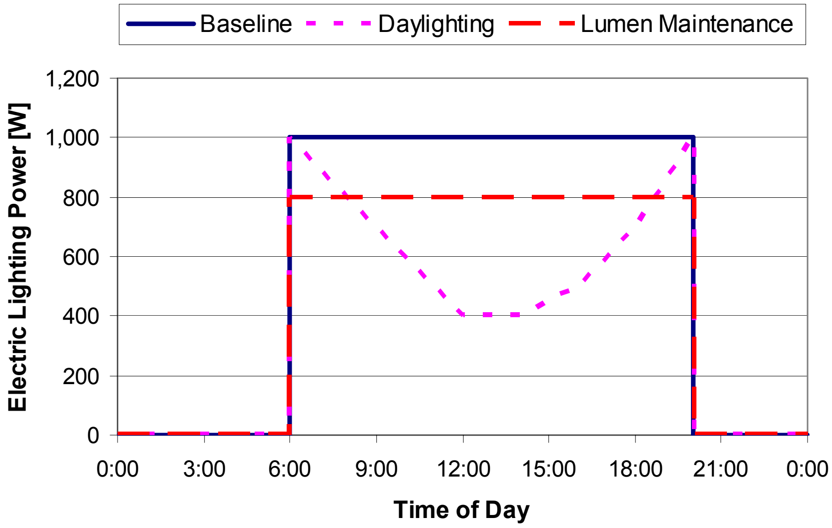

Figure 9-16: Illustrative Light Power Level Reductions from Photosensor-Based Electric Light Dimming Control as a Function of Time of Day

Daylighting reduces electric lighting output in response to the amount of available daylight in the space. Naturally, this strategy works best in portions of buildings that receive a lot of daylight, such as perimeter areas with windows or areas with skylights.

A lumen maintenance strategy reduces the initial illumination of a new system to the designed minimum level. By design, the output of new lighting systems exceeds minimum illuminance levels by 20 to 35%. This allows for the gradual decrease of light fixture output over time due to lamp lumen depreciation (degradation of bulb efficacy[166]; see Figure 9-17), luminaire dirt accumulation, and room surface dirt accumulation. As lamp output decreases, the photosensor detects the decrease in light levels and increases the lamps' output in order to maintain constant illuminance. The result is that the lamps operate at full power only toward the end of their lives, which reduces the energy consumed by the lamp (IESNA 2000).

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[166] The lumen depreciation varies significantly different light technologies. For example, an older T12 fluorescent lamp may degrade by a bit more than 20% over its rated lifetime, while a standard T8 lamp degrades by a little more than 10% (New Buildings 2003).

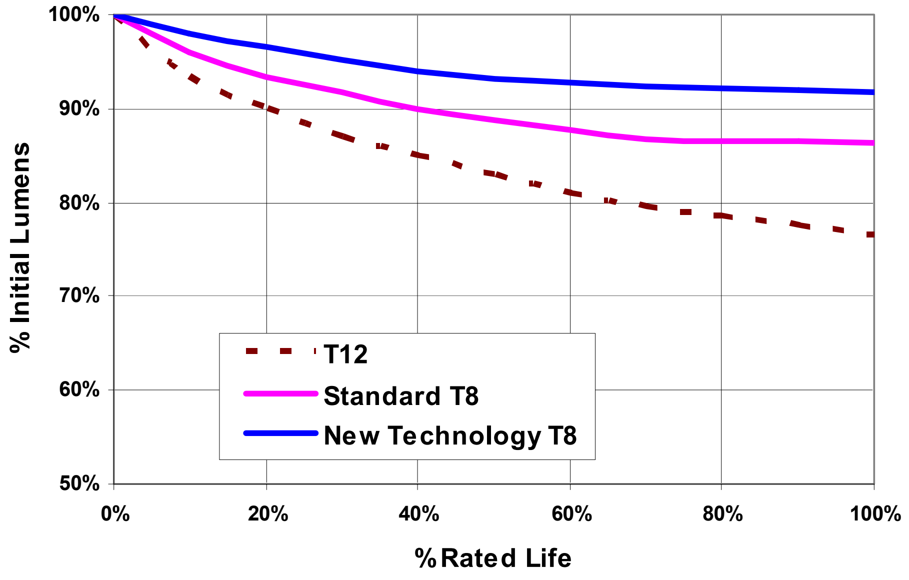

Figure 9-17: Representative Fluorescent Lamp Lumen Depreciation (based on New Buildings 2003)

Building design plays a crucial role in determining the potential to apply daylighting in a given space. Some architectural features that are used to manage indoor distributions of daylight include blinds, shades, light shelves, and awnings. In some cases, light pipes are used to bring light into more central portions of buildings. Interior features, such as cubicle partitions (and their heights) and surface reflectances, can also have a substantial impact on daylighting efficacy. Dimming of lighting fixtures in response to daylight from perimeter windows is typically limited to fixtures less than roughly 12 feet from windows, beyond which point relative darkness may result for some occupants (PG&E 1997). If the building design does not effectively manage daylight, direct beams of sunlight may cause glare and very high contrast in interior light levels, both of which may cause occupant dissatisfaction. Therefore, an effective daylighting design will manage the daylight such that it provides more diffuse light during the course of a day. In general, daylight from skylights is easier to coordinate with electric lighting than light from windows because it yields more similar light distributions, i.e., both originate from the ceiling area.

Two types of photosensors exist: illuminance sensors and luminance sensors. Table 9-44 describes the advantages and disadvantages of each type of photosensor.

Table 9-44: Photosensors and Their Advantages and Disadvantages (based on LRC 2001)

Photosensor	Advantages	Disadvantages
Illuminance	• Wide field of view results in an optical signal representative of average illuminance of entire workplane (ceiling-mounted sensor) • Normal room activity does not affect the optical signal	• Ceiling illuminance does not usually correspond to workplane illuminance, as the amount of daylight changes during the day; photosensor control algorithms can overcome this issue.
Luminance	• A narrow field of view effectively tracks illuminance change on target surface (if surface has constant reflectance properties) • Advantageous for maintaining light levels on a limited-area workplanes	• Very high sensitivity to changes in reflectance of objects within field of view, e.g., a dark desktop with white papers, a white shirt with a dark suit, moving furniture, etc.

Photosensors used for dimming control can be divided into two main types: open loop and closed loop. In an open-loop system, the photosensor does not “see” the electric light that it controls and, thus, do not incorporate feedback about the actual light levels served by the dimmed lamps. Consequently, the system cannot correct for any changes in the light distribution that affects the ratio between indoor and outdoor light levels, such as the use of window blinds (LRC 2001). An outdoor photosensor controlling the dimming of indoor electric lights in proportion to outdoor daylight levels is an example of an open-loop system. In a closed-loop system, the photosensor senses the actual light level in the spaces served by the dimming lamps and modulates the electric light output. This feedback loop compensates for an increase in the input signal (space light level) by decreasing the output signal to the controller, while a decrease in input signal increases the output signal. The amount of feedback varies for different systems and different mounting locations[167] of the photosensor. The strength of feedback also depends on the space geometry and surface reflectances. For example, a room with dark-colored finishes will have a smaller feedback gain than a room with light-colored (i.e., more reflective) finishes (LRC 2001).

Photosensor sensitivity depends on two gain mechanisms: optical gain and electronic gain. The optical gain is characterized by the spatial sensitivity (sensitivity to radiation from different directions) and the spectral sensitivity (sensitivity to radiation of different wavelengths). The electronic gain amplifies weak signals from the light-sensing element to practical signal levels. Open-loop systems require sensitivity adjustments for commissioning of a photosensor to ensure that all elements of the system interact effectively according to the design intent to meet the space lighting needs. Ideally, a photosensor should have a spectral sensitivity very similar to that of the eye. If not, space light levels can diverge from those intended. For example, if a photosensor used in conjunction with daylighting responds to a greater portion of the light spectrum than the human eye, it will

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[167] For example, systems with the photosensor mounted near a window have more moderate feedback than systems with the photosensor mounted in the middle of the same room. That is, photosensors located near windows receive a higher ratio of daylight to electric light, so that the photosensor “sees” proportionally less of the electric light that it controls.

perceive more light than the human eye and the daylighting system would tend to result in low indoor light levels (as perceived by its human occupants).

Photosensor placement is crucial to the effective implementation of photosensor-based daylighting control. A photosensor can be an integral part of a luminaire or remote from the luminaire that it controls. Alternatively, it can control a circuit relay that controls several luminaries. The appropriate use of a photosensor depends on placement, and calibration. Table 9-45 lists the four most common locations of photosensors.

Table 9-45: Common Photosensor Placement Locations (based on IESNA 2000, New Buildings 2003)

Location	Notes	Relevant Energy Management Strategies
On a Task Surface	• Directly measures task illuminance • Possible difficulties wiring sensor to controller • Need to ensure that task objects or space occupants do not damage or cover up sensor	Lumen maintenance
On the Ceiling	• Most common placement • Can provide light level measurements for either workplane surface or room (average) • Usually does not get direct sunlight	• Daylighting • Lumen maintenance
Near Fenestration (includes Skylights)	• Measures actual level of daylight entering through fenestration • Best results obtained if sunlight does not fall directly on the sensor	Daylighting
Building Exterior	• Measures external illuminance directly • Rough correlation with indoor light levels • Often used for outdoor lighting on-off control • Need to avoid shading	Daylighting (challenging)

When controlling interior lighting with photosensors, the amount of area covered by each photosensor is a key consideration. All of the areas controlled by a single photosensor should have the same general task activities, i.e., illuminance requirements and similar daylight illumination conditions (both amount and direction).

Compared to manual on-off controls, dimming controls generally increase energy savings, align lighting better with user needs, and can extend lamp calendar life with proper controls. Building occupants may not notice lighting dimmed by as much as 50%, unless they are conducting tasks requiring visual acuity (WSU 2000). Dimming ballast reduce lamp output by decreasing the current flowing through the lamp while maintaining required operating voltage levels (see, for example, IESNA [2000] for a discussion of approaches). Newer dimming ballasts installed for energy-saving purposes can typically dim lamp output to as low as 5 to 10% of full output; more-costly architectural products can dim down to as low as 1% (New Buildings 2003). The power draw reduction percentage from dimming is always less than the reduction in light output, however, because the ballasts consume energy, even at 0% dimming[168] (New Buildings 2003).

Photosensors for dimming control came to market more than twenty years ago. Nationally, they are used in approximately 5% of all commercial buildings (accounting for 11% of all commercial building floor space; EIA 1999). Their use in new buildings may be greater, e.g., a California study that interviewed 158 facility managers, electrical engineers, and architects where found that daylighting photosensors were utilized in 14% of new commercial construction and 12% of retrofit commercial construction (DiLouie 2004). In practice, photosensor-based lighting control usually only serves a fraction of the space in a given buildings. For example, e.g., RLW Analytics (1999) estimates that continuous photosensor-based dimming systems control less than 1% of the lighting loads in new California school, office, retail, and public assembly buildings. Furthermore, most systems appear to be non-continuous dimming systems (RLW Analytics 1999, PG&E 2000 from RLW Analytics 2000). Consequently, in all likelihood, the percentage of commercial floor space that is actually served by continous dimming photosensors is likely less than 1%. Therefore, despite having been available in the market the last twenty years, photosensors have realized very limited market penetration (PG&E 2000). The explicit inclusion of “daylight responsive” controls in the recently released LEED-CI specification (USGBC 2004) could stimulate greater use of daylighting controls.

9.9.3 Performance Benefits

In many daylighting applications, photosensor-based control can increase lamp calendar[169] life because it reduces the average number of daily lamp operating hours. Increased lamp calendar life reduces lamp replacement frequency and lamp maintenance costs, which include lamp purchases and the labor to replace lamps. Field evidence suggests that the impact on operational lamp life of frequent on-off switching of fluorescent lamps, which may occur in buildings located in climates that experience frequent changes in daylight levels, varies for each lamp-ballast combination and the on-off frequency. In general, frequent on and off switching of fluorescent lamps tends to reduce their operational life (in hours), but the reduced energy expenditures generally exceed increases (if any) in maintenance cost even if the calendar life decreases (New Buildings 2003).

Another benefit is that dimming systems used in conjunction with utility communication systems offer a potential means of reducing peak electric demand by dimming lamps (LRC 2001). Studies suggest that building occupants usually do not notice at least a 20% to 30% gradual (over several seconds or more) reduction in lighting levels (Akashi 2004).

9.9.4 Energy Savings Potential

A wide range of estimates exist for the energy saving potential of photosensor-based lighting control. Daylighting can reduce the lighting energy consumption in perimeter

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[168] Up to 6W for a two-lamp ballast (New Buildings 2003).

[169] Calendar life refers to the time that a lamp will last in real-time hours instead of operational hours.

offices with windows by 30% to 40% energy savings between 6am and 6pm, while daylighting that uses light from skylights can realize even greater reductions, typically 40% to 60% (New Buildings 2001, New Buildings 2003). Automatic daylight dimming has been shown in field studies to result in energy savings between 10% and 60% for private offices, with an average annual energy savings of approximately 27% (Jennings et al. 2000). Initial findings of a photosensor project suggest annual energy savings of 30% of the light fixture energy (LRC 2003). It is important, however, to remember that these savings only apply to areas of buildings that receive adequate daylight for daylighting from windows or skylightights. Very limited data suggest that the percentages of total commercial building floor space receiving sufficient dayllight from windows and skylights equal approximately 15% to 20% (LRC 2001, PG&E 2000) and 2% to 5% (PG&E 2000), respectively. Limited field experience suggests that lumen maintenance can reduce lighting energy consumption by between 5% and 15%[170] (see Section 9.9.2; EPA 2001). In sum, photosensors for automatic indoor light dimming control has a national energy savings range of 0.4 to 0.8[171] quads of primary energy. This assumes that buildings do not incorporate additional skylights. Single-story buildings account for about 40% of all commercial floorspace (EIA 1999), which indicates the potential for greater use of skylights and correspondingly larger reductions in lighting energy consumption.

In practice, however, most installed daylight-linked systems appear to not provide the anticipated energy savings (Galasiu 2004, Torcellini et al. 2004). This can be attributed to improperly installed or commissioned systems, use of darker indoor materials that reduce light reflections, and systems that have been overridden by occupants. A study conducted in Ottawa, Canada of daylight-linked photosensor controlled lighting systems found that window blind configuration can greatly affect the energy savings of photosensor-controlled dimming systems, decreasing the energy savings by 5% to 45% (Galasiu 2004). In all cases, energy savings depend on correct location and commissioning of the photosensor for each space.

Aside from reducing lighting energy demands, daylight dimming can also lower cooling loads by reducing the heat generated by the lights. Cooling equipment could potentially be downsized by as much as 5% for zones with daylight dimming systems (WSU 2003, Reed et al. 1995). On the other hand, reductions in lamp output also reduce internal building loads during the heating season and, thus, increase heating loads. An analysis by Sezgen and Koomey (1998) indicates that reductions of lighting energy consumption in commercial buildings have a negligible net impact on national HVAC primary energy consumption. The cooling equipment down-sizing benefits – if implemented concurrently – still remain.

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[170] If lumen output decreases by 10% to 30% over a bulb's lifetime, the energy savings will be approximately half of the change in output, i.e., 5% to 15%.

[171] For the 80% of spaces that cannot effectively use daylighting, lumen maintenance savings of 5% to 15% apply = 4.2 quads * 80%* (5% to 15%) = 0.17 to 0.5 quads. For the remaining 20% that can use daylighting, savings of about 30% apply = 4.2 quads * 20% * (25% to 30%) = 0.21 to 0.25.

9.9.5 Cost

A typical single-circuit photosensor control circuit for a fixture with three fluorescent T8 lamps[172] costs approximately $50 from the distributor and the dimmable ballast accounts for at least 80% of the total cost (Lighting Research Center 2003; Architectural Energy 2003). In contrast, the (non-dimming) instant start ballast, which has captured over 85% of the electronic ballast market, has an OEM cost of approximately $10, or less than $15 from a distributor (LRC 2003; Architectural Energy 2003). As a result, dimming ballasts purchased through a retailer cost about three times more than conventional instant start ballasts, i.e., about $80 versus $25 (Architectural Energy 2003). Taking into account an additional $5 cost[173] per fixture (LRC 2003), photosensor systems have a total incremental end-user equipment cost of around $60[174] relative to standard non-dimming equipment (Architectural Energy 2003). According to at least one industry expert (Petrow 2004), much lower production volumes (almost 100-fold; Architectural Energy 2003) and decreased competition account for most of the cost difference between instant start and dimming ballasts.

These costs, however, do not include labor for wiring or commissioning costs. Inherently, photosensor-based lighting control has a wide cost range that reflects the various sizes of the load controlled and differences in implementation complexity. New Buildings (2003) reports a cost premium of \$0.75 to \$1.75/ft^2, which implies simple payback periods of approximately 12 to 28 years[175], not taking into account peak electric demand reductions. Another study collected cost information for retrofit installations and commissioning of dimming systems for four commercial locations (see Table 9-46). The dimming systems equipment cost include one photosensor, one controller per zone, and one dimming electronic ballast to replace each standard ballast. The labor cost includes the time required to install the system plus half a day of labor for testing and tuning the system. These data suggest even longer payback periods for dimming ballast systems.

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[172] According to LRC (2003), this is the most common fixture used in commercial building new construction or renovations.

[173] Assuming consistency with the text, this represents retailer cost.

[174] Because the dimming ballast accounts for most of the system cost, using a photosensor to control multiple ballasts would not appreciably reduce the system cost. In fact, the need to relay the control signal from the photosensor to each ballast increase installed cost.

[175] Assuming a baseline lighting density of 1W/ft^2 and 2,600 operating hours per year, a dimming system that achieves a 30% reduction in lighting energy consumption would save \$0.06/ft^2 annually for an electric rate of \$0.08/kWh. For a dimming system with a \$0.75/ft^2 cost premium, the daylighting system would have a simple payback period of about 12 years.

Table 9-46: Dimming System Costs (includes markups; XENERGY 2001)

Installation Description	Number of fixtures controlled	Labor [$/fixture]	Equipment [$/fixture]	Total Installed [$/fixture]	SPP[176] [years]
Baseline: Single Office – High Volume	2	$63	$68[177]	$131	N/A
Single Office – High Volume	2	$230	$373	$604	74
Single Office – Low Volume	2	$270	$437	$707	90
Baseline: Open Floor Plan – High Volume	10	$63	$58	$121	N/A
Open Floor Plan – High Volume	10	$101	$148	$249	20
Open Floor Plan – Low Volume	10	$107	$174	$281	25

This indicates that dimming systems are currently not cost-effective due to high dimming ballast cost and high commissioning and installation costs. This clearly points out the importance of decreased dimming ballast costs and rapid-commissioning systems.

9.9.6 Barriers

Photosensors for lighting dimming control have not successfully captured their potential market share because of four major barriers: the high cost of the dimming ballast, the complexity in installing and commissioning the photosensor system correctly, lack of evidence that the technology works reliably and provides cost-effective energy savings, and the need to consider daylighting during building design for effective implementation.

The foremost barrier to greater use of photosensor-controlled dimming is the first cost (DiLouie 2004, LRC 2003). Installation and commissioning costs, including additional hardware and wiring, are high and make it difficult to achieve attractive simple payback periods in many applications. Notably, dimming ballasts cost up to four times more than standard, on-off ballasts. As noted earlier, much lower (~100-fold) production volumes and decreased competition account for most of the cost difference between instant start and dimming ballasts.

The second barrier is the complexity of correctly installing (photosensor placement) and commissioning (also known as calibration) the photosensor system. These processes are crucial to effective system operation, notably for daylighting systems, and time-consuming, which increases implementation cost. Photosensor placement has a major impact on system function, i.e., the light "seen" by the photosensor needs to correlate well with the light distribution under a wide range of conditions within the space controlled by the

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[176] Assuming three 34W T8 lamps per fixture, 2,600 hours of operation per year, $0.08/kWh, and 30% energy savings.

[177] The reference appears to have switched the low-volume and high-volume equipment costs.

photosensor, particularly on work surfaces. Consequently, sensor placement often requires customization to each space to reflect the light distribution characteristics in the space as function of both time of day and time of year (New Buildings 2003). Software packages[178] exist that can help to analyze daylight distributions over the course of the year and make appropriate sensor placement decisions, but they do not appear to be used often because of their complexity and user interface issues (Rubinstein 2004). In addition, the instructions for placement of photosensors are often written in generalities and the exact location left to the contractor, who may or may not have experience with the technology (WSU 2000). In many cases, lighting designers lack sufficient familiarity with daylighting systems and provide inadequate or faulty design documentation (e.g., specifications, control parameters) that compromises system efficacy (Vaidya et al. 2004). Additionally, photosensors may be located for aesthetic reasons rather than control purposes (WSU 2000).

Commissioning of commercially available photosensors is complex and time consuming (LRC 2001), and typically requires trained technicians to adjust and calibrate the controls (PG&E 2000). In particular, daylighting-based lighting control requires calibration under both midday and twilight conditions to ensure acceptable light levels at work surfaces under varying conditions (New Buildings 2003). Commercial photosensors use analog technology that requires manual adjustment of sensor sensitivity to establish the dimming algorithm that maintains a constant level of illumination of work surfaces. This tends to be a tedious trial-and-error process that often consumes a prohibitively large amount of time (LRC 2003, LRC 2001). Recently, a photosensor that includes a handheld remote[179] for wireless adjustment of sensor settings to facilitate commissioning has come to market. Furthermore, a prototype of a new self-commissioning photosensor has been developed (LRC 2003; LRC 2004). It comprises a wall-switch controller and a remote, wireless self-powered sensor. The photosensor commissions itself automatically with the press of a button in less than two minutes based on measurements of workplane and ceiling illuminance. Neither, however, directly addresses sensor placement challenges or the high cost of dimming ballasts.

Another complication in terms of commissioning is that the same signal level from a photosensor can produce different dimming levels with different ballasts (LRC 2003). The DALI standard address this issue and offers the potential to mix and match DALI components from different manufacturers. DALI has had market success in Europe, but has yet to have a major impact on the United States market (LRC 2003).

The third barrier is a lack of evidence that photosensor technology works reliably and provides low-risk payback. Facility managers and building owners do not believe automatic dimming is cost-effective and they are wary of possible reliability issues (LRC 2003). In practice, many daylight-linked systems do not provide the anticipated energy savings

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[178] Many software tools use an interface that works with the program RADIANCE to perform light distribution calculations. See p. 4-33 of New Buildings (2003).

[179] See: http://www.wattstopper.com/products/details.html?id=110 .

(Galasiu 2004, Vaidya et al. 2004) due to improper installation, commissioning, as well as occupants overriding systems. For example, a case study of six high-performance buildings that all used daylighting found that the photosensors did not function properly with the lights (Torcellini et al. 2004). Currently, a lack of tools complicates up-front assessment of daylighting energy savings. For example, an experienced designer of daylighting systems indicated that no single software program provides hour-by-hour simulation results of daylight distribution levels in spaces that can be used for energy calculations. Instead, his company uses a separate daylight prediction program and links the results into a whole-building simulation program (Zubizarreta 2004).

Problems also persist with building occupant satisfaction because many systems do not maintain sufficient lighting levels (typically due to poor calibration). Consequently, occupants do not receive enough light and become frustrated with their lack of control over the lighting. This can lead to disabling of the photosensor-based lighting control (LRC 2003, Vaidya et al. 2004). Furthermore, anecdotal reports from the field suggest that lamps can fail prematurely when operated on dimming ballasts (LRC 2001). Properly selected modern rapid start and programmed start[180] ballasts may eliminate this problem (Rubinstein 2004).

Fourth, effective and pleasing daylighting requires the integration of daylighting into building design. This, in turn, requires the architect to consider daylighting during the building design phase (at the latest) and collaborate with the lighting contractors to implement effective daylighting. Accurate daylighting calculations for design purposes require careful modeling of the daylit spaces, including not only the daylight entering the space throughout the year but room features that impact daylight distribution, including walls, partitions, floors, soffits, furniture, and the light-related qualities of these surfaces. Several software and hardware (scale models, mock ups) tools exist that enable building designers to consider how different layouts affect indoor daylight levels over the course of a year. These can help architects to create buildings with daylight-friendly features and lighting designers to develop effective daylighting control designs, e.g., to identify appropriate control zones and circuits based on areas with similar daylight contours over the course of the day and the year (New Buildings 2003). This takes time and care to set up properly. Further software development, such as the SPOT tool[181], may improve the ease of obtaining basic results, but it is not clear that it can appreciably reduce the time and expertise required to set up daylight simulations unless it can readily accept input from design programs[182].

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[180] Lamp cathode failure is the primary failure mechanism for fluorescent lamps. Both of these approaches preheat the cathode for a period to generate ions before striking an arc in the tube. As a result, the voltage required to strike the arc decreases relative to an instant start ballast (often used for nondimmable fluorescent lamps), which, in turn, decreases cathode wear (Rubinstein 2004).

[181] SPOT runs in Microsoft Excel and provides hourly daylight value distributions throughout a space (based on RADIANCE). At present, it can only simulate daylighting for spaces with simple geometries and cannot accept Autocad files. More information is available at: http://www.archenergy.com/SPOT/index.html .

[182] For example, in .xml format (see: http://www.gbxml.org/about.htm).

Common building design practices, however, often impedes the collaboration needed for the integration of daylighting into building design (see Sections 5.2 and 5.3) and can lead to poor or even contradictory daylighting-based lighting control (Vaidya et al. 2004, New Buildings 2003). Improperly implemented daylighting can admit very high levels of sunlight that cause glare and result in very high contrast in interior light levels that may distract occupants and make them uncomfortable. New Buildings (2003) is one of several sources that discusses the challenges of and provides recommendations for successfully implementing daylighting.

9.9.7 Technology "Next Steps"

Although photosensor-based lighting control has been commercialized for about twenty years, it still serves a very small portion of commercial building floorspace. Overcoming the high cost of dimming ballasts is relatively straightforward, i.e., it appears to largely depend on increasing production volume and is not a technical issue. Nonetheless, it is essential to achieving widespread use of dimming ballasts. Properly placement and effective commissioning of photosensors for lighting control, particularly for daylighting applications, are major design and implementation challenges because effective sensor placement and daylighting both are space-specific and depend greatly on building design. The following next steps address these two major barriers:

1. *Improved Software Tools for Photosensor Placement and Energy Impact*: This tool would address the challenges of proper photosensor placement and effective building daylighting design. Current daylight simulation tools do not combine detailed (spatial and temporal) daylight calculations with building energy calculations. Development of a user-friendly tool that provides this functionality could increase photosensor-based lighting control for daylighting by facilitating effective building daylighting design (better understanding of daylight distributions in spaces), improving ease of proper photosensor placement, and providing quality energy impact data to assess space-specific cost-benefits. The SPOT tool appears to facilitate evaluation of photosensor placement and potential daylighting energy savings for simple spaces, but cannot model more complex and "real" spaces.
2. *Increase Dimming Ballast Production Volumes* – Even if buildings incorporate effective daylighting design and photosensor placement and commissioning become routine, current high dimming ballast costs will continue to impede market deployment. Low manufacturing volumes appear primarily responsible for large cost premiums; hence, efforts should focus on measures that increase manufacturing volumes, such as market promotion and purchasing incentives.
3. *Field Demonstration and Market Promotion of Products that Expedite Photosensor Commissioning*: This step would decrease the implementation cost of photosensor-based lighting control systems by reducing the time to commission the controls. At least one product to expedite photosensor commissioning has recently come to market. Widespread use of these products, including self-commissioning sensors and sensors that can be commissioned from the ground through a simple interface, will reduce the time to commission photosensors. In turn, this would increase commissioning quality and occupant acceptance of photosensor-based lighting control.

4. *Daylighting Design and Implementation Guidance* – Tools can facilitate - but are not substitutes for - effective design and implementation of daylighting systems. Often, daylighting suffers from several design and implementation problems that result in subpar system design and system performance. This, in turn, leads to occupant dissatisfaction with the systems and reduced energy savings. Broad diffusion of succinct and comprehensive "best practice" guidelines for the effective design, installation, and commissioning of daylighting systems to all parties involved in daylighting implementation is needed to improve the quality of installed daylighting systems. As suggested by Vaidya et al. (2004), such guidelines should focus on process and incorporate checks to insure that correct implementation occurs from design through implementation.

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9.10 Automated Whole Building Diagnostics (WBD)

9.10.1 Summary

Automated whole building diagnostics (AWBD) is a form of ongoing commissioning (see Section 9.1) that compares top-level information about building energy consumption (e.g., electricity, gas, chilled water) to an appropriate baseline to assess whether or not a building and its systems operate efficiently. AWBD encompasses a range of techniques. For example, a simple embodiment would compare annual energy consumption per square foot for the building to values established for similar buildings (size, climate, and type). A more complex variant might perform virtual real-time comparisons of actual building energy consumption with detailed models of expected building energy consumption that reflect the expected energy consumption of key building systems under current environmental conditions and usage patterns. When building energy consumption exceeds the baseline value by a sufficient margin, the tool flags the building energy consumption as high and often provides information or carries out procedures (such as functional testing) that help to home in on the cause of the excess energy consumption. On a national basis, AWBD has an upper-bound energy saving potential comparable to ongoing commissioning, or roughly 0.5 to 1.8 quads. In practice, AWBD can only diagnose a few major faults, such as "HVAC and Lighting Left On When Space Unoccupied." On the other hand, AWBD can facilitate the detection of a broad range of faults that significantly increase whole building energy consumption.

In addition, AWBD can increase equipment life, improve occupant comfort, and decrease maintenance costs. Tools that incorporate AWBD functionality have begun to come to market but have very little market share and face several barriers to achieving significant market share. Foremost, building operators and owners express limited interest in AWBD tools. When told about the tools, they tend to doubt the operational and cost effectiveness of the tools. More sophisticated AWBD tools would likely cost too much for buildings that do not have well over 100,000 ft^2. Other problems include insufficient data points for more sophisticated AWBD, insufficient data storage capability in many existing EMCS, and concerns about excessive false alarms.

Table 9-47: Summary of Whole Building Diagnostics

Characteristic	Result	Comments
Technology Status	Current to Advanced	Some tools commercially available; all tools still under development
Systems Impacted by Technology	HVAC and lighting, larger refrigeration	
Readily Retrofit into Existing Buildings and Systems	Yes	Implementing a diagnostic tool may require additional measurement and communications hardware
Relevant Primary Energy Consumption [quads]	9.2	HVAC, lighting, and 50% of refrigeration energy
National Technical Energy Savings Potential [quads]	0.5 – 1.8	Upper bound for AWBD that reflects energy savings range for commissioning; in practice, AWBD can only diagnose a few, large faults but can help to detect many others
Non-Energy Benefits	Improved building control, increased equipment life, improved occupant comfort ,and decreased maintenance costs	
Approximate Simple Payback Period [years]	Wide variation	Depends greatly on floorspace served by tool; in general, much shorter SPP for very large buildings (several hundred-thousand ft^2) campuses
Key Economic Barriers	First cost	Software costs, additional hardware costs (sensors), implementation/setup time. Most cost-effective when installed in buildings with an EMCS (EMCS serve ~10% of commercial buildings, 33% of floorspace; EIA 1999).
Key Non-Economic Barriers	Lack of proven performance	
Key Enabling Technologies	Low-cost wireless sensors, EMCS	Wireless reduces cost of additional data points in existing buildings; EMCS facilitates data acquisition
Notable Developers of Technology	CANMET (Canada), Facility Dynamics, PNNL, Texas A&M; Major controls vendors offer building energy monitoring services	
Peak Demand Reduction?	Yes	
Most Promising Applications	Very large buildings or campuses with limited operating hours that require high volumes of outdoor air (mitigates scheduling and outdoor air intake faults)	
Technology "Next Steps"	• Rigorous field evaluations of AWBD tools to evaluate the costs and benefits of implementation • Development of AWBD-only tools targeted for smaller buildings • Develop standard format for reporting building data (structure and building system design) for easy importation into whole building simulation models • Continue development of NILM-based AWBD	

9.10.2 Background

A whole building diagnostics (WBD) tool is a software program that takes a ”top-down” approach to diagnostics to detect excess energy consumption of the whole building and its major systems, such as HVAC, lighting, and large refrigeration systems (Ivanovich 1999). That is, WBD compare electricity, gas, steam, or chilled water energy consumption data, typically at the building level (see Table 9-48) to an expected *baseline* level to detect meaningful changes in building energy consumption. As such, WBD is a subset ongoing commissioning performed using only building-level energy data (see Section 9.1); the project team identified as a separate approach for evaluation based on its appreciable energy-saving potential and relative simplicity.

Table 9-48: Whole Building Diagnostic Levels

Level	WBD?	Example
Campus	Yes	Campus steam consumption
Building	Yes	Building electricity consumption
Building Wing	Possibly	Chilled water consumption
Zone	No	Lighting panel power draw
Equipment	No	Air handler power draw

Friedman and Piette (2001) characterizes diagnostic software tools as either manual or automated diagnostics. Manual diagnostic tools help a building operator to extract information from collected data, e.g., via raw data visualization of summary or time-series data (see Section 4.2.4 for further discussion of data visualization methods). For example, a user could compare historical, monthly, daily, or real-time whole building electricity consumption to a reference level calculated for that building based on a performance model or benchmark values from that building or another building under similar operating conditions. They require an experienced operator who can identify problems based on inspecting information and graphs generated automatically by the software.

Automated fault detection and diagnostic (AFDD) tools typically use the same data as manual tools and may also carry out functional tests[183]. In contrast to manual diagnostic tools, AFDD tools replace human data analysis and interpretation with software-based synthesis that attempts to mimic human analytical procedures (e.g., via statistical methods or expert rules see section 4.2.1). They use these procedures to detect and diagnose problems and, potentially, provide a list of appropriate solutions without user intervention. They have particular value for less experienced operators or operators with little time to spend on data interpretation. The rest of this section focuses on automated WBD (AWBD).

The discussion of AWBD will follow the diagnostic steps outlined by Friedman and Piette (2001), that is:

1. Building data acquisition.
2. Data storage.
3. Data evaluation to detect potential problems.
4. Data analysis for problem diagnosis.

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[183] Functional testing puts selected systems through a series of operational procedures and compares system behavior to the intended behavior to evaluate system performance. The tool uses the information to detect deviations from expected performance, i.e., faults, and then diagnose the fault's cause. Section 9.1.2 includes examples of functional testing.

Data Acquisition

An AWBD tool acquires time-series data of multiple measurement points. For cost reasons, AWBD tools typically acquire data from a building's existing EMCS when available instead of installed a dedicated data acquisition system. Many tools also require entry of one-time set-up information such as building and equipment schedules, temperature setpoints, plant configurations, etc. In many cases, tools require different routines to acquire data from different EMCS (Friedman and Piette 2001), which can complicate data acquisition. The data can be stored in a database for the tool, either onsite at the building or forwarded to an offsite location (e.g., via the Internet) for remote storage and analysis.

Data acquisition includes both passive measurement of whole building energy consumption, as well as measurements from active testing, such as functional testing or blink tests[184]. Active tests facilitate identification of the energy consumed by specific equipment or systems, which, in turn, enable more precise fault detection and diagnostics. In all cases, it is crucial that the AWBD tool receives high-quality data to permit meaningful performance assessments. Hence, AWBD setup typically requires a basic level of building commissioning (see Section 9.1).

Data Storage

Once the tool has received the data, the tool archives (saves in memory) and pre-processes the data. AWBD tools usually keep a historical record of building energy performance – preferably at least a year of data – to develop meaningful comparative energy consumption baselines (see discussion of baselines below). In addition, data are often pre-processed to increase their utility for fault detection and diagnostics. Pre-processing can include time stamping data, validating that the data lie within pre-determined (reasonable) ranges, calculating higher-level metrics (e.g., btu/ft^2), and re-creating or filling in missing data (Friedman and Piette 2001).

Fault Detection and Diagnosis

After acquiring and validating data, the tool detects and diagnoses faults. To detect a fault, the software tool compares a building performance metric, such as whole building or equipment power draw, to a baseline level adjusted to reflect current operating conditions defined by key explanatory variables, such as outdoor air temperature and relative humidity, insolation levels, and time of the year, week, or day. If the difference between the metric and the baseline exceeds a threshold, the system determines that a fault has occurred. Several different possible baselines for whole building energy exist (see Table 9-49). In general, the table presents the baselines in order of increasing complexity (and, hence, cost). More complex approaches are not used nearly as much as the simpler approaches due to their complexity, as well as building data and tool user time requirements.

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[184] During a blink test, the building operator turns off a specific building system, such as a lighting bank or an AHU, and notes the decrease in whole building electricity (or gas, chilled water, steam, etc.) consumption. The decrease equals the magnitude of that load and helps to identify that load in future whole building energy analyses.

Table 9-49: Potential Whole Building Energy Baselines (based on Haves et al. 2001)

Baseline Type	Characteristics
Comparable Buildings – Previous Performance	• Based on statistically-representative buildings • Uses regression models to adjust energy for geography, building type, and floor space • Provides general assessment of qualitative energy use, i.e., high, typical, or low • Typically used over longer timescales
Comparable Buildings – Current Performance	• Compares energy performance of similar buildings in close to real-time, e.g., hourly to weekly basis • Most often used by organizations with many buildings, e.g., campuses or chains • Uses regression models to adjust energy for geography, building type, and floor space • Enables more timely detection of abnormally high energy consumption
Same Building – Previous Performance	• Compares current and past energy performance of same building • Uses “calibrated simulation” to account for differences between baseline and current conditions • Typically uses either a first-principles (e.g., EnergyPlus) or empirical (neural network) to model building performance • Can help identify efficient operating approaches
Same Building – Intended Performance	• Compares actual performance to intended performance Intended performance modeled by whole building simulation program, such as EnergyPlus or DOE-2 • Several challenges to successful modeling of building: limited input data (particularly with respect to building loads), differences between simulated and actual equipment and controls behavior/performance • Very complex and computationally intensive

Researchers also have proposed using neural networks to develop a model that predicts the power draw/energy consumption of building systems and equipment based on explanatory variables, such as OA temperature, time of day, day of the week, etc. (see Section 4.1 for further discussion of neural networks). For example, Dodier and Kreider (1999) used a type of neural network called belief networks[185] to make probabilistic assessments of excessive energy consumption, which could be used to detect faults. Neural networks usually require at least a couple of weeks of high-quality training data to develop the coefficients for the relationships and, thus, require commissioning prior to implementation to insure data quality and proper system function (Mahling 2004).

Monitoring of whole building electricity, gas, steam, or chilled water consumption can help to detect the possible existence of larger faults, i.e., those that increase whole building energy consumption by at least 5% (Claridge et al. 1999; see Table 9-50). Importantly, whole building electricity measurements often can reveal high electricity or gas energy consumption after normal operating hours, which suggests improper HVAC or lighting schedules that lead to after-hours operation, the fault with the greatest national energy impact (see Section 8.3).

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[185] Belief networks establish probabilistic models for the values of different variables of different parts of a system given the values of the variables of other system parts. A good summary of belief networks is available at: http://www.anc.ed.ac.uk/~amos/belief.html .

Table 9-50: Examples of Faults Detected by Evaluation of Whole Building Energy Consumption (from Claridge et al. 1999)

Fault	Comment
HVAC and Lighting Operation During Unoccupied Hours	Compare night/weekend electricity consumption to that during occupied periods
Valve Leakage	Comparing actual and expected steam usage
Simultaneous Heating and Cooling	Comparing actual and expected steam and chilled water* usage during cooling season
Inefficient Chiller Plant Operation	Comparing actual and projected chilled* water usage
*For a campus building having a central campus plant.	

The diagnosis of other faults, however, usually require further, more targeted investigation to identify the equipment or system(s) with higher energy consumption and, ultimately, the fault responsible for increased energy consumption (see Appendix 9.10.8). That is, AWBD may be capable of detecting the presence of a fault but cannot diagnose the fault. For example, AWBD may detect increased building electricity consumption due to an economizer damper failure that causes excess outdoor air intake. It would also note that electricity consumption increased during the day, which could lead the tool user to investigate cooling system performance. Ultimate detection of the failed damper, however, would require closer examination of measured values that can pinpoint the failure, e.g., outdoor air temperature, return air temperature, and mixed air temperature (see Section 9.2). Diagnosis of the root cause of the failed damper (broken linkage, stuck damper, etc.) may only be possible upon examination of the damper. Some tools with AWBD incorporate the requisite functionality to carry out diagnosis of equipment-level faults (see Table 9-51).

Existing AWBD Tools

Although research to develop diagnostic tools and methods for building HVAC systems began more than a decade ago, only recently have software tools become available (Friedman and Piette 2001). Table 9-51 lists three commercially available tools with AWBD capability, the building systems they serve, and some of the faults that they can detect from whole building energy consumption data. Overall, AWBD represents a relatively small portion of the functionality of two of the tools. In addition, several controls vendors offer remote building energy monitoring services[186] that effectively function as AWBD tools. Other AWBD tools likely exist, notably for commissioning purposes.

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[186] For example, see: http://www.johnsoncontrols.com/cg-energy/perform_optimize.htm .

Table 9-51: Diagnostic Tools Inputs and Detected Faults (based on Friedman and Piette 2001, Motegi et al. 2003a)

Diagnostic Tool (Developer)	Input From Following Systems	Faults Detected by System
Facility Explorer (Johnson Controls)	Whole Building Energy	• High or low whole energy consumption relative to prior baseline data for that building
PACRAT (Facility Dynamics Engineering)	Whole Building Energy	• Utility deviation from baseline • Unoccupied operation
	Other	• Economizer / Air handling unit • Central plant (chiller) • Distribution (hydronic) • Zone control
Whole Building Diagnostician (PNNL)	Whole Building Energy	• Electric and gas consumption deviation from baseline
	Other	• Economizer/AHU function • Central plant and distribution

Noninvasive Load Monitoring (NILM)

Noninvasive load monitoring (NILM) represents an alternative approach under development (but not yet commercialized) to detect whole building faults. It analyzes electric voltage and current measurements at the equipment scale or larger to detect changes in electric power draw and infer operational problems. A NILM-based tool used with equipment-level submeters goes through a training period to develop mathematical models for the relationships between electric power draw and building measurements, such as outdoor air temperature (T_{OA}). As with all training periods, properly-functioning systems and quality measurements are essential to develop meaningful data. NILM uses three approaches to detect faults. First, the tool compares actual equipment operational status[187] and power draw with expected values for current operating condition and signals a fault if the difference exceeds a confidence-based detection threshold. Second, the tool scans the electrical measurements for higher-than-expected power oscillations that can indicate control issues or hardware problems (e.g., leaky dampers) under some conditions. Third, the tool compares higher-speed measurements (16 kHz) of motor start-up characteristics with system models. If the transient behavior falls outside of the model range, the tool can detect mechanical problems. Submeter-based NILM tools have the potential to detect and diagnose a range of faults for dampers, cooling coil valves, sensor drift, and controller tuning (Shaw et al. 2002, Luo et al. 2002).

A NILM tool that measures whole building electricity applies the first two strategies discussed in the prior paragraph to detect problems involving loads that account for at least 5% of the monitored load, e.g., a large AHU, chillers, or a large lighting circuit (Shaw et al. 2002, Luo et al. 2002, Lee et al. 2003). On the other hand, the decreased resolution of a

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[187] Includes equipment cycling

larger scale, e.g., whole-building electricity, makes it more difficult for those tools to detect problems. Diagnosis of problems using larger-scale NILM is particularly difficult because the measurements reflect the contributions of several pieces and different kinds of equipment. Even if an electronic signature could be traced to a particular type of equipment, the system currently cannot link specific pieces of equipment with loads if the meter serves more than one piece of equipment with similar loads (Shaw et al. 2002). The ability of NILM-based tools to detect multiple faults is not clear.

9.10.3 Performance Benefits

A conventional EMCS continuously acquires building performance data and can automatically flag anomalous equipment operations through any alarms established by building operators. Otherwise, overall building performance monitoring only occurs when a building operator reviews top-level energy data, e.g., as compared to prior values for that building. Typically, in neither case are energy data adjusted to reflect key explanatory variables or geographical location, building type, and buidling floor space. In contrast, automated tools continuously and automatically monitor building data and performance to baselines adjusted for the building's context. This reduces the operator skill and time required to detect performance problems while increasing the probability of detecting problems. Consequently, in addition to saving energy, AWBD can reduce peak electricity demand and demand charges, increase equipment life, improve occupant comfort, and decrease maintenance costs (Friedman and Piette 2001). Earlier detection and remediation of faults decreases the time that equipment and systems operate in a faulty condition, which often increases equipment life and reduces maintenance costs (e.g., by preventing excessive cycling). Prompt remediation of faults also improves building climate control, which improves occupant comfort. Furthermore, AWBD can reduce emergency service calls and catastrophic equipment failure by providing feedback on equipment and system states. Since automated diagnostics can track repair histories as well as fault occurrences, building owners and mechanical contractors can make better "repair or replace" decisions. In all cases, however, this assumes that the building operator or maintenance personnel fix the faults soon after detection and diagnosis. This does not always occur.

In the future, diagnostic tools may detect problems, make reliable diagnoses, relay the diagnosis to a service contractor, and direct these contractors in the repair/replacement of components (Haves and Khalsa 2000). Thus, AWBD can lead to more effective use of technician's labor. If diagnostic recommendations are provided to technicians before they arrive on site, the technicians could better plan their work time (e.g., have the right parts available, thereby avoiding multiple trips to the location to work on the same problem). .

9.10.4 Energy Savings Potential

The energy-saving potential of retro–commissioning represents an upper bound on AWBD energy savings. Thus, it could reduce building energy consumption by as much as 5 to 20%

(see Section 9.1), or 0.5 to 1.7 quads when applied to HVAC, lighting, and half[188] of refrigeration energy. In practice, AWBD can only detect faults when they result in a significant increase in whole building energy consumption and actually diagnose but a few faults (e.g., HVAC and Lighting Left On When Space Unoccupied). This limits the practical energy saving that stand-alone AWBD can achieve. On the other hand, AWBD can facilitate the detection of a broad range of faults.

It is important to note that AFDD does not automatically save energy, i.e., the tool user must investigate the cause and take the necessary steps to fix the problem.

9.10.5 Cost

The actual cost of a fully implemented AWBD tool[189] depends on several factors, including its sophistication, the presence (or absence) of an EMCS, existing measurement points, and data quality. In general, implementation costs usually exceed tool costs for more sophisticated tools (Friedman and Piette 2001; Motegi et al. 2003b, Smith 2003). Commissioning of automated diagnostics tools, particularly for larger systems and custom-designed built-up systems, often requires a substantial amount of skilled labor (VTT 2001; see Section 4.5.2 for further discussion).

Tool cost generally increases with tool capabilities and the degree of automation. For example, the least expensive tools generally only provide data archiving and pre-processing. The most expensive tools provide data acquisition, archiving, pre-processing, and fault detection and fault diagnosis for a wide range of faults in different systems (see the PACRAT entry in Table 9-51). Whole building simulation programs are complex and, hence, costly to incorporate into tools, while incomplete or insufficient building system, equipment, and control models in the simulation programs further complicate their usefulness (Haves et al. 2001, PECI 2003). Greater complexity also increases the time needed – and the cost – to implement more sophisticated tools. For example, software-related costs, including tool configuration[190] and training account for most of the cost to implement sophisticated tools that also have AWBD capability (Friedman and Piette 2001; Motegi et al. 2003b).

An EMCS usually provides access to key data points, which decreases implementation costs. If a separate data acquisition infrastructure is required, this further increases cost.).

If tool implementation requires additional measurement points, such as temperature sensors or insolation levels (for sophisticated tools; Haves et al. 2001), this increases tool cost by an average of approximately $600 per measurement point. Additional points can add in excess

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[188] This represents the approximate fraction of refrigeration energy attributed to larger refrigeration systems, namely supermarket refrigeration systems and walk-in system (ADL 1996).

[189] Data are not available for existing AWBD tools because AWBD functionality represents only a portion of the tools' capabilities.

[190] In this case, configuration denotes the initial installation of the tool in the building and integration with the EMCS, including any customization required for the existing building.

of $10,000 to the cost of a more sophisticated system (see Section 6.1; Xenergy and Nexant 2002; Motegi et al. 2003b). Notably, many EMCS do no provide real-time utility data, i.e., building electric power draw, gas flow, steam flow, and chilled water flow. The AWBD tool could tap into the existing utility meters to measure their pulsed outputs and convert that signal to real-time energy consumption values (although this can prove costly because it requires the utility's permission; Mahling 2004). If the EMCS provides all the points required, however, additional hardware costs could be small.

Data quality issues can also increase implementation costs. A large portion of installations suffer from poor quality and/or missing data points and difficulties in importing data from the EMCS into the tool (Friedman and Piette 2001, Santos 2004). To ensure that the tools have quality data to function effectively, AWBD setup typically requires a basic level of building commissioning to ensure data quality and effective tool use. For example, tools require quality outdoor air temperature measurements (a key explanatory variable) that can be compromised by either either poor sensor placement or performance (Mahling et al. 2004, Piette 2004). In other instances, the tool cannot easily extract information from a building's EMCS because the EMCS uses a different communications protocols than those known by the AWBD[191]. To obtain the necessary information in such cases, the AWBD would need to use middleware to translate communications between the EMCS and the tool, which increase implementation costs.

In general, the cost of AWBD tools should be generally similar to those of energy information systems (EIS), which have similar data requirements, data visualization capabilities, and software costs, and can incorporate AWBD capabilities. Table 9-52 summarizes the installed cost breakdowns for EIS tools from three case[192] studies.

Table 9-52: Installed Costs for an Energy Information System (from Motegi et al. 2003b)

Application Context	Case 1	Case 2	Case 3
Application	4.5 Million ft^2 University Campus	100kft^2 Office Building	175kft^2 Office Building
Cost Component	**Cost**	**Cost**	**Cost**
Software License[193]	$181,000	$12,500	$16,000
EMCS Gateway	$12,000	N/A	N/A
Additional Sensors	$50,000	$41,500	$23,500
Installation/Setup	$52,000	$73,000	$73,000
Annual Maintenance	$35,000	N/A	N/A
Networking	$11,500	$9,000	$9,000
TOTAL	$341,500	$136,000	$134,000
$/ft^2	$0.10	$1.36	$0.77

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[191] An EMCS with integral AWBD capability would not have this problem.

[192] Case 2 and Case 3 used the same EIS tool.

[193] Some developers charge an additional cost for software upgrades, e.g., equal to 18% of the software's first cost for one sophisticated tool with AWBD capability (Friedman and Piette 2001).

Many cost components, such as the software tool, do not vary linearly with floorspace, making AWBD implementation more attractive in larger buildings than small buildings. As shown in Table 9-52, building size (square footage) has a major impact on the cost-effectiveness of AWBD tools, i.e., total costs ranged from \$0.10 for a 4.5 million ft^2 college campus to \$1.36/ft^2 for a 100,000ft^2 office building (Motegi et al. 2003a, Motegi et al. 2003b). Consequently, an AWBD that achieves a 20% reduction in building HVAC energy cost would pay back in about one year for the campus but closer to ten years for the office building. In sum, AWBD is most attractive for very large buildings or campuses with central DDC systems (Friedman and Piette 2001).

The NILM approach may be able to reduce the installed cost of AWBD because it uses a single measurement point to monitor the performance of larger building systems. The developer estimates that each electrical flow monitored by a NILM will have the same first cost as a submeter. Costs estimates vary widely, i.e., from \$200 to \$500[194] (Architectural Energy 2002) to \$1,650[195] per meter (Nexant and Xenergy 2002). On the other hand, NILM should only reduce sensor-related costs (see Table 9-52), which would moderate the *percentage* reduction of implemented tool cost.

9.10.6 Barriers

Four major barriers impair AWBD from achieving significant market share: a lack of awareness of AWBD, concerns about its cost effectiveness, insufficient data points and insufficient data storage capability from existing EMCS, and concerns about excessive false alarms.

A lack of awareness of is the foremost barrier to greater use of AWBD. Several reasons lie behind the lack of awareness. Currently, most building owners do not know how AWBD can improve building comfort and reduce energy consumption and cost. A relatively recent market characterization study found that many potential users do not even realize that diagnostic tools exist (Friedman and Piette 2001). This is due, in part, to the fact that only a few diagnostic systems developed have actually come to market as stand-alone product. Most of the research, development, testing and prototyping have occurred in research environments, such as laboratories and universities, with a few exceptions (Katipamula et al. 2003). The more sophisticated tools (such as PACRAT or the manual diagnostics tool EEM Suite) are primarily used in large buildings or campuses with central DDC systems (Friedman and Piette 2001).

AWBD is also perceived as a risky investment by potential purchasers and users of AWBD tools, as well as those who would provide building services[196] in response to problems diagnosed by the tools. A focus group evaluation of the Whole Building Diagnostician tool

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[194] \$200 represents the estimated incremental installed cost for a NILM circuit board installed in advanced electric meters (manufacturing volume of 10,000s), while \$500 represent their estimate of the installed cost for a stand-alone device.

[195] The meter costs \$1,150, installation an additional \$500.

[196] This includes technical resource managers, maintenance technicians, and people who work on automation systems.

revealed that product developers must demonstrate their tools in buildings that their customers can relate to in order to overcome the skepticism towards the product's capabilities (Heinemeier et al. 1999). Building operators also harbor concerns about the applicability of diagnostic tools to *their* buildings, i.e., that a tool designed for use in many building types would work in their building. Participants in the focus group had specific reservations about the ability of diagnostic tools to save energy cost and time and recommended performing demonstration projects to decrease their uncertainty about the tools' effectiveness. In part, this also stems from a lack of case studies that thoroughly quantify the benefits and costs to implement AWBD in buildings.

AWBD requires relatively few data point, most notably whole building electricity, gas, stream, and chilled water consumption, temperature setpoints, and key explanatory variables, such as outdoor air temperature, schedule information, time of the day and year. More sophisticated models, notably simulations, may require additional data, such as insolation levels. Nonetheless, data issues, including poor quality and/or missing data points and a lack of data trending and storage capability, impair AWBD implementation in many instances. Insufficient data points is a common problem and can prevent diagnosis altogether unless additional measurement points are added, most notably for whole building energy consumption simulations generated for almost real-time comparison with actual whole building energy consumption (Haves et al. 2001, PECI 2003). Adding additional measurement points, in turn, increases the cost of diagnostics implementation (see Section 6.1). Even if an EMCS has the required data points for a diagnostic tool, inferior data quality can impair effective function of a diagnostic tool. For example, an EMCS may have improperly commissioned sensors or sensors that have fallen out of calibration (see Section 9.5), which can lead to improper diagnoses. Many EMCS do not have enough data storage capability to collect sufficient data points over a sufficiently long period of time conduct diagnostics based on long-term performance trends (Friedman and Piette 2001). Tools that store relevant data in their own database can overcome this problem. Similarly, the cost of data storage has decreased dramatically over the past several years, which could easily be incorporated into an EMCS. Until very recently, however, this is generally not implemented in the field, presumably because EMCS vendors have historically placed a much greater emphasis on building control than performing building diagnostics.

Some AWBD tools also require manual importation of data from the EMCS, which usually runs on a different computer (Friedman and Piette 2001). This time-consuming inconvenience decreases the user-friendliness of those tools. Differing data formats can also impede the exchange of data needed for trend analysis (Santos 2004) or whole building energy consumption simulations (Haves et al. 2001). For AWBD tools that would use whole building simulation programs, such as DOE-2 or EnergyPlus, the sheer complexity of the simulation programs (and the resulting time and knowledge required to set up and modify the programs) inhibits their use for diagnostic purposes. Incomplete or insufficient models of building systems and equipment and building controls in whole building simulation programs further complicates effective use of the programs (Haves et al. 2001, PECI 2003).

Concerns about false alarms deter building operators from implementing diagnostic systems. Correct selection of thresholds is crucial in balancing fault detection sensitivity against the rate of false alarms (see Section 4.2). A tool must have a very low probability of false alarms; otherwise, building operators will doubt the tool's value and may decide that the aggravation of investigating false alarms outweighs the potential benefits of the tool. False alarms can be reduced by having the diagnostic tool determine when it lacks sufficient information to make a diagnosis (Heinemeier et al. 1999). The possibility of false alarms and thresholds with diagnostic tools is an important issue that requires further development.

In addition, some HVAC professionals and service technicians fear that computers will eliminate their jobs, as diagnostic systems can run continuously and do not require sleep, take breaks or go on vacation. Similarly, some HVAC professionals feel and resent that diagnostics systems can be used, albeit indirectly, to monitor their performance and find their mistakes (Ivanovich 1999).

9.10.7 Technology "Next Steps"

AWBD tools exist but most buildings do not use even basic benchmarking tools to assess annual energy consumption, e.g., the EnergyStar® buildings benchmark tool. In addition, most buildings also do not have access to real-time utility energy consumption data (Mahling 2004), which prevents comparison of real-time energy consumption to prior energy consumption. Furthermore, high-end tools, such as those that compare building energy consumption to that calculated by almost real-time simulations, are very rare and their expense prevents economic deployment in all but the largest buildings (or groups of buildings). "Next steps" need to raise building operator awareness of existing building tools, build their confidence in using tools, and reduce tool costs, particularly for smaller buildings. AWBD integration with whole building simulations must overcome data acquisition and modeling challenges and does not appear near to commercialization. If commercialized, however, it could enable more subtle fault detection – but not necessarily fault diagnostic – capabilities.

1. *Market Promotion of Benchmarking Building Energy Performance:* The EnergyStar® Target Finder tool[197] allows building operators to benchmark their building's energy consumption relative to other buildings in a given location for several different building types. Although it has substantial limitation, promotion of this tool or development and promotion of a somewhat more sophisticated (i.e., that takes into account actual water and space heating fuels and HVAC system types) that is also free and easy-to-use would allow owners to quickly assess whether or not their building consumes excessive quantities of energy.
2. *Rigorous Field Evaluations of Existing AWBD Tools*: Thorough evaluations of the costs and benefits of implementation will decrease the risk of investment in tools perceived by potential users. Activities should include evaluation and

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[197] See: http://www.energystar.gov/index.cfm?c=target_finder.bus_target_finder .

documentation of energy savings, cost, ease of implementation, frequency of false alarms, and non-energy benefits. Field evaluations should be performed for tools in target building markets, such as larger (>200,000ft^2) office buildings.

3. *Development of Cost-Effective AWBD-only Tools Targeted for Smaller Buildings*: Buildings under 50kft^2 accounted for almost half of all commercial building energy consumption in 1999 (EIA 1999) and tools that cost-effectively address this portion of the market are needed. Benchmarking can provide low-cost information about overall levels of building energy consumption, but more sophisticated tools that compare energy consumption to prior energy consumption under similar conditions are needed to identify many major faults. Approaches that tap into utility meters to compare real-time energy consumption data with past data have promise to accomplish this at lower cost. A large portion of smaller buildings do not have an EMCS, which complicates data acquisition and storage. Continuing decreases in the cost of data acquisition and storage could increase the cost-effectiveness of this approach in the future, e.g., integrated into EMCS-like products.
4. *Further Development and Field Testing of NILM-based Diagnostics*: Centralized NILM has the potential to provide virtual real-time identification of excessive energy consumption at the whole building and equipment level at relatively modest cost (because it does not require equipment submetering). NILM is an immature fault detection technology that requires further refinement to effectively function in actual buildings. Targeted field testing would help to identify its efficacy and issues that arise when it is applied to different kinds of HVAC systems.
5. *Develop a Standard Format for Building Data*: A process to report building data (structure and building system design) in a standard format that can be readily imported into whole building simulation models, such as DOE-2 or EnergyPlus would facilitate the use of whole building simulations to perform almost real-time assessments of actual versus intended performance. Some work is in progress to create standard data formats (see PECI 2003). This would not address, however, issues related to actual versus modeled building operation, nor the cost of additional data points.

9.10.8 Appendix – Fault Diagnostics

As discussed at the beginning of this section, WBD tools enable detection of faults that have a significant impact on overall building energy consumption but diagnosis of the faults responsible for increased energy consumption usually requires further effort. This Appendix outlines basic ways to diagnose faults whose energy impact is initially detected by WBD. Almost all methods use equipment- or system-specific data.

Raw data visualization is the most basic method of detecting faults. Building operators can detect faults manually by reviewing time-series data plotted using the methods shown in Table 9-53. For example, a user could compare actual chiller performance to historical or expected performance under similar conditions (e.g., outdoor temperature).

Table 9-53: Manual and Automated Diagnostic Methods in Diagnostics Tools (based on Friedman and Piette 2001)

Manual	Use	Description
Reference Line	Detection	Compares actual performance with appropriate reference performance (e.g., from system model)
Benchmarking	Detection	Comparison of (usually building-level) data with data taken from other buildings
Performance Metrics	Detection	Calculated summary values, e.g., COP or kW/ton
Statistics	Detection	Generates top-level values for variables: maximum, minimum, average, standard deviation, etc.
Automated	**Use**	**Description**
Diagnostic Rules	Detection	Decision tree based on expert knowledge and basic principles used to detect and diagnose faults
Modeled Baseline	Detection	Compares actual performance to historical baseline formulated through a model
Energy Cost Waste	Detection	Calculates energy waste cost
Expert Rules	Diagnosis	Rules developed from field experience

Diagnostic tool development has focused on detecting problems with central cooling (e.g., Haves and Khalsa 2000), heating plants (Hyvarinen 1996), and air handling units (e.g., Choiniere and Corsi 2003, Katipamula, Brambley, and Luskay 2003, Miyata et al. 2003, VTT 2001, Hyvarinen 1996), since these systems typically consume more energy and have greater instrumentation than other systems. Other diagnostic research efforts have targeted equipment and system components whose evaluation of performance is, to a large extent, self-contained, notably packaged rooftop units (see Section 9.8) and VAV boxes (Choiniere and Corsi 2003, Miyata et al. 2003, Schein and House 2003).

More sophisticated diagnostics use models of specific systems. Some researchers have developed energy signatures for how common (typically central) systems behave when they have a fault, such as excess OA, simultaneous heating and cooling, high duct static pressure, VAV systems performing as CAV systems, etc. (Claridge et al. 1999). These signatures allow an experienced practitioner – or, in the case of automated diagnostics, a FDD program – to compare actual with expected performance to diagnose faulty operation. In theory, a commissioning agent (person) or an FDD system could alter the building's operation to mimic certain building faults and develop energy (and, likely, other building performance variables) signatures for each fault. In practice, it is unlikely that an agent or FDD program would have sufficient time or opportunity to alter building operation in this way to generate sufficient data for each fault, particularly if this data were to serve as the primary method for detecting faults.

All of the prior methods have been passive schemes that detect faults by monitoring system performance. Proactive fault detection uses functional testing to check system functionality (see Section 9.1.2).

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10 Conclusions and Recommendations

10.1 Conclusions

TIAX carried out a study for the U.S. Department of Energy, Office of Building Technology (DOE/BT) to evaluate the energy saving potential of controls and diagnostics for commercial buildings through improved operation of energy-consuming building systems such as HVAC, lighting, and larger refrigeration systems. Overall, controls and diagnostics have the potential to realize large reduction in the approximately 17 quads of primary energy consumed each year by commercial buildings. Diagnostics provide the opportunity to reduce energy consumption by eliminating the gap between sub par system performance and as-intended performance, i.e., the energy impact of *faults*. Of course, non-diagnostic measures, such as improved maintenance practices or closer attention to operations, could also achieve some of the same energy savings as diagnostics. More sophisticated controls, on the other hand, enable additional savings above and beyond as-intended performance of building systems.

Almost all commercial buildings have at least very basic on-off control functionality to provide lighting, e.g., lamp fixtures controlled by light switches or a circuit breaker, and heating, e.g., a furnace controlled by a thermostat. In addition, many commercial buildings have time-based controls to turn on and off lighting and vary space conditioning at specified times of day, particularly when buildings are unoccupied. Over the past 25 years, direct digital controls (DDC) using software-based controllers have come to market, driven by dramatic increases in computing power and the concurrent miniaturization and cost decrease of computing power. This has greatly increased the flexibility and potential sophistication of building controls while decreasing their implementation cost, a trend that continues with current movement toward control communications over enterprise networks.

The combination of greater sophistication and lower cost has the potential to make a wide range of energy-saving controls approaches, including automated diagnostics, economically viable. Nonetheless, more sophisticated building controls and diagnostics have had limited success in penetrating the $3 billion (per year) building controls market in the U.S. For example, centralized energy management and control systems (EMCS) serve only about 10% of commercial buildings (33% of floor space), while occupancy sensors for lighting control serve well under 10% of all commercial building floor space. In buildings that do have an EMCS, many operators primarily use the EMCS for basic plant control functions but do not exploit more sophisticated capabilities, i.e., most operators only use a portion of available EMCS functionality. Furthermore, it appears that most EMCS are not integrated with other building systems. Energy-related building and equipment diagnostics, including building commissioning and basic comparative benchmarking of annual building energy consumption, have a very limited market share.

The following sections highlight key conclusions about the energy impact of subpar building system operations, the energy saving potential of controls and diagnostics, barriers to building controls, and drivers for building controls.

The Energy Impact of Faults

A literature review identified more than 100 faults that occur in commercial building HVAC, lighting, water heating, and refrigeration systems that may increase building energy consumption. TIAX developed preliminary annual energy consumption (AEC) estimates for each fault and used these estimates to identify thirteen faults for further evaluation (see Table 10-1). For each fault selected, the project team assessed the quantity of commercial building energy consumption potentially impacted by the fault, how often the fault occurs such that it causes an appreciable increase in annual primary energy consumption (AEC), and the average percent increase in energy consumption due to the fault. The product of these three factors equals the fault's AEC.

Together, the faults increase commercial building primary energy consumption by approximately one quad, or about 11% of energy consumed by HVAC, lighting, and larger refrigeration systems[199] in commercial buildings. Three faults, "HVAC Left on When Space Unoccupied," "Lights Left on When Space Unoccupied," and "Duct Leakage," account for about two-thirds of the total energy impact of the key faults (see Table 10-1).

Table 10-1: The Annual Energy Consumption Impact of Faults Selected for Evaluation

Fault	AEC [quads[200]]
Duct Leakage	0.30
HVAC Left on When Space Unoccupied	0.20
Lights Left on When Space Unoccupied	0.18
Airflow Not Balanced	0.070
Improper Refrigerant Charge	0.070
Dampers not Working Properly	0.055
Insufficient Evaporator Airflow	0.035
Improper Controls Setup / Commissioning	0.023
Control Component Failure or Degradation	0.023
Software Programming Errors	0.012
Improper Controls Hardware Installation	0.010
Air-Cooled Condenser Fouling	0.008
Valve Leakage	0.007
TOTAL	1.0

The estimated likely range of the energy impact is quite broad, i.e., between 0.34 and 1.8 quads. This bottom-up estimate for the overall magnitude of building faults is broadly consistent with the 5% to 20% energy savings potential range reported in the retrocommissioning literature. Placed in the context of commercial buildings, the faults account for between 2% and 11% of all energy consumed by commercial buildings. Considering only systems primarily affected by the faults, that is, HVAC, lighting, and

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[199] Larger refrigeration systems include supermarket refrigeration systems and walk-in system.

[200] One quad equals a quadrillion, i.e., 10^{15}, btus. All energy data shown in the table are primary energy data, that is, taking into account the energy consumed at the electric plant to generate electricity.

large refrigeration system energy consumption, fault-related energy waste equals between 4% and 20% of the energy consumed by those end uses.

Most of the fault energy impact estimates have a high degree of uncertainty, most notably controls-related faults for central HVAC systems. In no case do the publicly available data support a detailed analysis of fault energy consumption that segments fault energy impact based on building type and geographic region (e.g., as presented in CBECS). Many data sources (typically the building commissioning literature) suffered from one more issue that increased the uncertainty in fault energy impact estimates, including: inconsistent reporting of faults between studies and inconsistent data formats or level of detail, a tendency for commissioning studies to focus on problem buildings, and a concentration of commissioning studies in certain parts of the country. The data to address these gaps likely exist, but not in the public literature, i.e., energy service companies (ESCOs) and utilities may have collected proprietary information to understand the cost-benefit relationship of different energy saving measures, including maintenance and commissioning. It is not clear, however, that this information would substantially alter diagnostic development priorities.

Energy Saving Potential of Control and Diagnostic Approaches

This study analyzed the energy saving potential of nine controls and diagnostics approaches. Other approaches not explicitly discussed in this report may also have significant national energy savings potential, such as variable-speed drives and EMCS. For each approach, the team assessed its technical energy saving potential[201], technical maturity, non-energy benefits, economics, barriers to commercialization, and development "next steps." Table 10-2 summarizes the technical energy savings potential ranges for nine of the approaches; HVAC sensors do not directly save energy. Overall, more sophisticated controls have a higher national technical energy savings potential than diagnostics.

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[201] Technical energy savings potential equals the annual energy savings if the technology were applied to the entire installed base of relevant equipment and systems.

Table 10-2: Control and Diagnostic Approaches Evaluated

Approach		Technology Status	Relevant Energy Consumption [quad]	Technical Energy Saving Potential [quad]
Diagnostics	Commissioning	Current / New	9.2	0.5 – 1.8#
	Damper Automated Fault Detection and Diagnostics (AFDD)	Current / New	0.85	0.02 – 0.1
	Duct Leakage FDD	Advanced	3.1	0.15 – 0.4
	Packaged Rooftop Unit AFDD	Advanced	0.74	0.025 – 0.14
	Whole Building Energy AFDD	Current / Advanced	9.2	0.5 – 1.8*
Controls	Demand Controlled Ventilation (DCV)	Current	2.7	0.3
	Occupancy Sensor-Based Lighting Control	Current	4.2	0.6 – 2.3**
	Optimal Whole Building Control	Current / Advanced	9.2	0.5 – 1.3***
	Photosensor-Based Lighting Control	Current	4.2	0.4 – 0.8
Enabling	HVAC Sensors	Current / Advanced	4.5	N/A

Commissioning may save all fault-related energy consumption, except possibly duct leakage.
*Saving from “Commissioning” represents an upper bound for both ends of the range.
**Could also eliminate unintentional “Lights Left on When Space Unoccupied,” saving 0.02 to 0.13 quads.
***Includes energy saved from elimination of unintentional “Lights and HVAC Left On When Unoccupied.”

That is, the potential energy saved from enhanced control of building systems exceeds that from eliminating sub-par operations. It is important to note that the energy saving potentials of different approaches may not be additive, as savings realized by an approach can decrease and/or preclude energy savings from other approaches. Nonetheless, a combination of selected controls and diagnostics approaches from Table 10-2 could reduce commercial building AEC by between 2.3 quads and 6.5 quads per year, or between 14 and 38 percent.

These data also provide insight into the energy savings achieved by controls operating at different scales (see Table 10-3).

Table 10-3: Energy Savings Potential by Control Scale

Control Scale	Energy Savings [approximate Range, %]	Representative Control Strategies
Room / Space	1.0 – 3.0	• Occupanacy-based Lighting Control • Photosensor-based Lighting Control
Zone	0.4 – 1.2	• HVAC/Lighting Scheduling • Economizer Control • Demand Controlled Ventilation
Building	0.5 – 1.3	• HVAC/Lighting Scheduling • Optimal Whole Building Control (OWBCS)
Multiple Buildings	Small	Coordinated peak shaving (including with OWBCS) (Note: primarily economic – not energy – benefits)

Room-level lighting controls, specifically occupancy- and photosensor-based lighting control, have large energy saving potentials and it is not clear that whole-building lighting-control approaches would realize appreciable savings beyond those from addressing the “Lights Left on When Space Unoccupied” fault. In contrast, most HVAC savings accrues from zone- and building-level HVAC controls. To a large extent, this reflects the reality (due to cost) that a limited number of buildings have HVAC systems capable of controlling space conditions at that small a scale. Recently, the concept of integrated building systems, i.e., systems that share information, has received considerable attention. It is not clear, however, that integrated building systems offer appreciable additional energy savings potential beyond the approaches described above. Specifically, many buildings lack the granularity of HVAC control needed to vary temperature setpoints in response to a worker’s presence or absence. On the other hand, it may offer the possibility to increase the *market-achievable* energy savings because sharing communincations infrastructure can reduce the installed cost building controls while also providing additional value to building operators.

Overall, some common themes arise as to how the nine controls and diagnostic approaches investigated reduce energy consumption (see Table 10-4).

Table 10-4: Common Themes to Energy Consumption Reduction

Energy Consumption Reduction Theme	Relevant Technologies
Automate Control Functions	• Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control
Eliminate Unnecessary Lighting	• Commissioning • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control • Automated Whole-Building Diagnostics
Eliminate Unnecessary Heating, Cooling and Ventilation	• Commissioning • Automated Whole-Building Diagnostics
Fault Detection and Diagnostics	• Commissioning • Dampers AFDD • Packaged RTU AFDD • Automated Whole Building Diagnostics
Reduce Excessive Outdoor Air Intake	• Commissioning • Dampers AFDD • Demand Controlled Ventilation • Duct Leakage Diagnostics • Automated Whole-Building Diagnostics

The economics of controls and diagnostics approaches have a major impact on their market attractiveness. The nine[202] approaches generally have broad simple payback period (SPP)

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[202] Figure 10-1 does not provide values for photosensor-based lighting control because, for continuous dimming systems, the SPP typically exceeds 10 years.

ranges (see Figure 10-1) that depend upon the specifics of particular applications. Notably, the SPP of centralized control or diagnostics approaches tends to be sensitive to the floor space impacted by the approach because relatively fixed costs account for a large portion of system installed cost. Thus, commissioning, optimal whole building control systems, and whole building AFDD will have better economics for larger buildings (e.g., several hundred thousand square feet) than smaller buildings. On a national basis, this limits their market-achievable energy savings, as buildings with less than 50,000ft^2 account for almost half of commercial building energy consumption. Analogously, room-level controls, such as occupancy sensors and photosensors for lighting control, tend to have shorter payback periods when they serve larger spaces and influence a larger quantity of energy consumption. In the case of diagnostics, the cost of diagnostics hardware, installation, and commissioning usually dominate their SPP, with the notable exception of retrofit duct leakage FDD, where the cost of fixing the fault (i.e., duct sealing) dominates the cost.

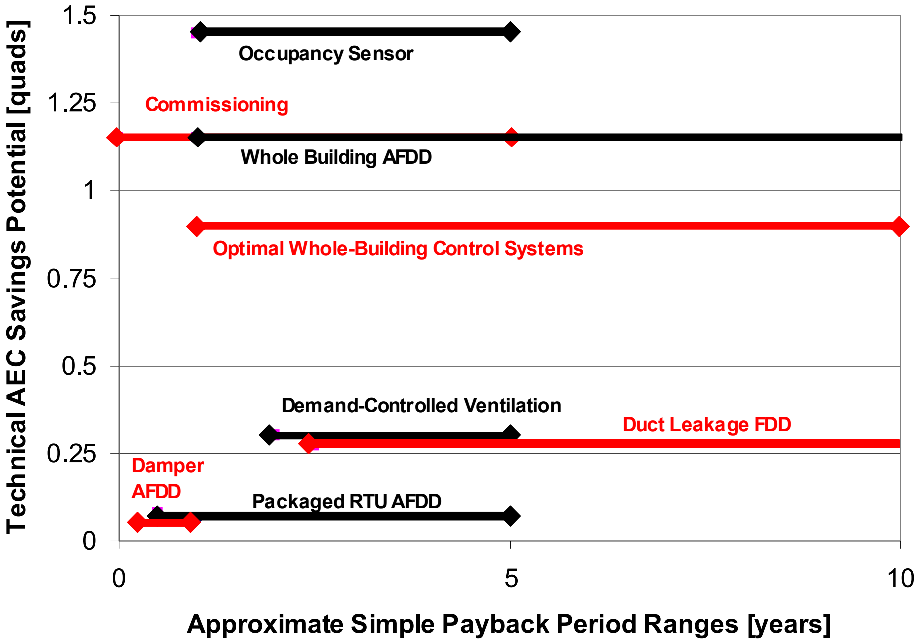

Figure 10-1: Estimated Technical Energy Savings Potential and Simple Payback Periods for the Options

Because these SPP ranges reflect average utility rates, approaches that reduce peak electricity demand, e.g., by reducing outdoor air intake, improving design-condition cooling and ventilation performance, or managing peak demand will have a shorter SPP in areas with higher demand charges. Although factory-installed equipment-specific diagnostics (such as packaged RTU and damper AFDD) have much lower energy saving potentials than centralized approaches, they appear to offer attractive SPPs.

Barriers to Controls and Diagnostics

To varying degrees, all controls and diagnostics options face real or perceived economic barriers to entering the market. These include general barriers to energy efficiency measures, barriers specific to controls and diagnostics, and approach-specific barriers.

A central issue for all energy savings measures is that energy costs represent only a small portion of expenditures for most buildings, e.g., about 1% of *total* annual expenditures for an office building. Consequently, most building owners and tenants place a low priority on reducing energy expenditures. For buildings that will be let, owners often have little incentive to increase energy efficiency because tenants usually pay for energy. Furthermore, energy efficiency measures compete directly for funds that could be invested in core business functions. Consequently, building owners need solid evidence of a quick payback period to consider making energy efficiency investments. Building owners and design professionals often believe that more sophisticated building controls carry greater financial risk than conventional controls, in large part due to insufficient examples and credible documentation of the costs, benefits, and operational experiences with different approaches.

The dominant new construction paradigms for commercial buildings also tend to impede the effective deployment of more sophisticated controls and diagnostics. The most common paradigm, design/build, fixes many design variables early in the process to enable different parts of the construction processes to overlap. Often, building controls are not considered until late in the construction process, when funds are scarce and most of the building infrastructure has already been specified. In that case, low-cost systems are “shoe-horned” into the existing infrastructure, creating a sub-optimal installation. Furthermore, the contractor who installs the controls may not be the same party who specified the controls, which also decreases the efficacy of controls. Recent modifications to the organization of the building construction process to include specific sections for communications and integrated automation in the MasterFormat™ specification could enhance the potential to consider and deploy more sophisticated controls approaches and integrate building systems.

In contrast, the collaborative construction model takes a broad view that emphasizes an integrated evaluation of design options. This increases the potential to achieve an energy-efficient building, including the use of building controls and diagnostics. On the other hand, this approach has a higher first cost and takes longer to construct than design/build and plan/design/build, which most building owners view as potent negatives. Overcoming these shortcomings will require dramatic changes in current building practice.

More sophisticated building controls and diagnostics also face general barriers to greater use, including the high cost of retrofitting controls in existing buildings and equipment, low levels of understanding by key decision makers, and interoperability challenges. Existing buildings accounts for about 75 to 80% of total building control expenditures. Retrofit installations often require additional sensors and new communications infrastructure, particularly for more sophisticated controls, which can be prohibitively expensive and also disruptive to the current occupants. This highlights the value of measures that decrease the installed cost of building controls, such as wireless communications. Because system installation accounts for approximately 70% of the installed cost of controls in new buildings, these measures can also benefit new construction.

A relatively low level of understanding of building controls and diagnostics by decision makers further inhibits deployment of more sophisticated controls. Not only do knowledge gaps impede their consideration, the gaps also form a cascade of sub par decision-making that compromises the efficacy of installed controls and diagnostics. When controls and diagnostics cannot realize their promised cost savings, this increases the perceived risk of controls and diagnostics investments and the reluctance of people to invest in those technologies. The evolution of building controls from pneumatic to electronic and digital has exacerbated this knowledge gap, and it is not clear that the current structure of the buildings industry can support the wages demanded by a software-centric building controls industry.

The commercialization of open communications protocols, such as BACnet™ and LonTalk®, in the 1990s promised to provide true interoperability between products offered by different vendors. In theory, this would increase competition for the provision of hardware and services and provide access to a wider range of functionality while reducing the first and ongoing costs of building controls. In practice, interoperability – and the benefits that it would provide – often remains elusive because adherence to standards and protocols that ensure interoperability among diverse systems does not generally exist for building controls.

Each specific controls and diagnostic approach faces specific barriers to attaining significant market share. Beyond high first cost, a lack of market track record represents the largest market barrier for several of the nine approaches, most notably for diagnostic approaches (see Table 10-5).

Table 10-5: Common Barriers Facing the Nine Controls and Diagnostics Approaches

Barrier	Relevant Technologies
Cost / Payback Uncertainty	• Wireless HVAC Sensors • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control
Difficult to Implement	• Commissioning (schedule issues) • Wireless HVAC Sensors (lack of guidance) • Photosensor-based Lighting Control (placement and calibration)
Higher First Cost ("current" technologies)	• Commissioning • Damper AFDD • Demand Controlled Ventilation (CO_2 sensor cost) • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control • Automated Whole Building Diagnostics

Lack of Industry Awareness	• Commissioning • Duct Leakage FDD (of prevalence of duct leakage) • Optimal Whole Building Control Systems
Reliability Concerns	• HVAC Sensors (CO_2, humidity / enthalpy) • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Photosensor-based Lighting Control
Unproven Performance	• Duct Leakage FDD • Wireless HVAC Sensors • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Packaged RTU AFDD • Photosensor-based Lighting Control • Automated Whole Building Diagnostics (more advanced approaches)

Finally, the first cost of centralized building controls and diagnostics inhibits their deployment in smaller buildings. A large portion of the cost of centralized approaches usually does not scale linearly with square footage. This usually results in a higher installed cost (on a $/ft^2 basis) for centralized measures in smaller buildings. In addition, smaller buildings tend to have fewer zones, require less sophisticated control, and may not reap the same energy and maintenance benefits from centralized control. Recently developed EMCS-like products offered by major building controls vendors targeting light commercial buildings that offer EMCS-like functionality and are designed for integration with and control of RTUs could improve the cost-effectiveness of more basic centralized controls and diagnostics in smaller buildings.

Key Opportunities for Greater Deployment of Building Controls and Diagnostics

Overwhelmingly, maintaining occupant comfort ranks as the main goal of buildings operation because it creates a more desirable working environment and improves tenant retention. The dominance of worker salaries in office building expenses indicates that building controls and diagnostics investments that enhance worker productivity or increase sales, even by only 1%, are very attractive investments. For instance, a 2% increase in the productivity of office building occupants has the same economic impact as eliminating *all* building operations and energy expenditures. In all cases, **building controls and diagnostics can greatly increase their value by enhancing the core business of the building – be it employee productivity or sales**. Similarly, building controls and diagnostics can also add value by preventing productivity degradation (e.g., from sick building syndrome) or lawsuits linked to poor indoor air quality (e.g., due to mold).

Prior research suggests relationships between productivity and several variables related to controls, such as personal climate control and outdoor air ventilation level. Although building tenants appear to highly value measures related to occupant comfort, the owner/operator must link tenant comfort to financial parameters such as productivity to make a convincing business case for substantial investments. From their perspective, however, the link between most building attributes, let alone building controls, and occupant productivity is not sufficiently well understood and documented to make a convincing business case for substantial investment.

Reducing energy expenditures is another, more moderate value proposition for building controls and diagnostics. Although utility expenses represent only 1% of total building expenses, they do account for about 30% of *operating* expenses. The potency of this value proposition depends on gas and electric costs, in particular, peak electric demand charges that account for approximately 40% of commercial building electricity expenditures (on average). Lighting and HVAC represent about 75% of commercial sector peak electricity demand and building controls have the potential to achieve substantial reductions of both end uses via peak-shaving functions, such as switching off portions of indoor lighting or allowing indoor temperature setpoints to rise during periods of notably high peak demand. Although many EMCS presently have the capability to implement measures that limit peak demand, only a small percentage of building operators with this capability use it.
Building maintenance expenses account for more than 20% of office building operating expenses. Consequently, controls and diagnostics measures that offer cost-effective reductions in maintenance expenses can prove attractive. For example, centralized building controls can be sold – and EMCS were initially installed – as a way to monitor building performance to reduce building maintenance and operations expenses. In theory, reduced maintenance and operations costs should decrease the payback period of controls and diagnostics. In practice, the payback calculations often only consider energy savings because maintenance savings are difficult to quantify.

Several of the nine controls and diagnostics approaches offer one or more of the non-energy benefits discussed (see Table 10-6).

Table 10-6: Common Non-Energy Benefits of the Nine Controls and Diagnostics Approaches

Non-Energy Benefit	Relevant Technologies
Ensuring Adequate Outdoor Air Intake	• Commissioning • Damper AFDD • Demand-Controlled Ventilation
Improved Occupant Comfort	• Commissioning • Damper AFDD • Duct Leakage FDD • Packaged RTU AFDD • Automated Whole Building Diagnostics
Notable Peak Demand Reduction	• Commissioning • Damper AFDD • Demand-Controlled Ventilation • Duct Leakage FDD • Occupancy Sensor-based Lighting Control • Optimal Whole Building Control Systems • Packaged RTU AFDD • Photosensor-based Lighting Control (daylighting) • Automated Whole Building Diagnostics
Decreased Maintenance Costs	• Commissioning • Packaged RTU AFDD • Automated Whole Building Diagnostics

Finally, technologies that reduce the installed cost of building controls and diagnostics can improve their economic attractiveness. All of nine options could be readily retrofit into existing equipment or buildings, which would allow them to penetrate the existing building stock much more rapidly than technologies primarily limited to new construction or major renovations. The cost of retrofitting many approaches, however, can be much higher than incorporating the approach in new construction. For example, factory integration of additional sensors and microprocessor capabilities in existing equipment, such as for damper AFDD or RTU AFDD, would cost much less than retrofitting diagnostics into equipment. In the case of centralized systems, installation, including wiring and electrical work, accounts for more than half of the installed cost; indeed, installation and commissioning account for at least 70% of total installed cost. Consequently, greater deployment of measures that significantly reduce the cost of installing controls, such as structured/shared cabling systems for building systems and cost-effective wireless sensors and communications, can improve the economic attractiveness of many more sophisticated building controls and diagnostics. Furthermore, the emerging practice using enterprise networks to also communicate controls-related information offers the potential to reduce cost by sharing communications infrastructure while also increasing functionality by facilitating information sharing between building and business systems. In the future, enterprise networks could also devolve some control of occupied space to building occupants by allowing input on space conditions, such as temperature and lighting. Prior studies have shown positive correlations between increased personal environmental control and increased occupant comfort, so this could enhance occupant comfort, the primary goal of building operators.

Wireless sensors and communications products have begun to enter the buildings market. For example, the “big three” building controls manufacturers all offer wireless temperature sensors that can be integrated with their controllers at prices that are competitive with wired installations. Ongoing efforts to develop low-cost and easy-to-implement wireless sensors and communications promise to improve the future economics of retrofitting controls and diagnostics in buildings. Recently, a wireless solution has come to market that provides pervasive indoor wireless communications access via radio frequencies for several different applications, including building controls. Building owners may install this solution primiarly to provide cell phone and Wi-Fi service in buildings, in which case building controls could leverage the wireless infrastructure. This would decrease the installed cost of wireless measurement points for building control.

In addition, the use of low-cost and high-accuracy MEMS-based sensors in the HVAC industry will enhance the prospects for greater deployment of diagnostics in new equipment and buildings. MEMS-based humidity and CO_2 sensors that increase sensor accuracy and reduce sensor maintenance could also increase the effective use of enthalpy-based economizers and demand-controlled ventilation, respectively.

10.2 Recommendations

At least two general and several technology-specific recommendations arise from this study. Two general recommendations to increase the deployment of more sophisticated controls and diagnostics in commercial buildings are:

- *Develop Rigorous and Credible Cost-Benefit Information for Diagnostics and Novel Building Controls*: These products are perceived as risky investments by building owners, operators, and building systems designers, which greatly decreases their market attractiveness. Thorough evaluations that fully account for the costs, benefits, and reliability are key activities to gain designer building owner confidence and achieve significant market penetration.
- *Research to Understand the Relationship Between Variables Influenced by Controls and Diagnostics and Productivity/Sales*: The sheer magnitude of the potential value from increased employee productivity provides the motivation for further research to understand and document the linkage between productivity and lighting, environment control, indoor air quality (IAQ), etc. Developing data that are sufficiently strong to develop a convincing business case is a very challenging endeavor that could, however, prove elusive even with substantial investments.

Owing to the different barriers and developmental stages of the nine controls and diagnostics approaches evaluated, efforts to promote widespread application of the approaches range from research to market transformation (see Table 10-7). Approach-specific recommended "next steps" are presented in Section 9.

Table 10-7: Technology Development Potential "Next Steps" for the Nine Controls and Diagnostics Approaches

Potential "Next Step"	Relevant Technologies
Research & Development	• Commissioning • Duct Leakage FDD • Optimal Whole Building Control Systems • Automated Whole Building Diagnostics
Education	• Commissioning • Demand Controlled Ventilation (clarification of ASHRAE Standard 62) • Duct Leakage FDD (problem of Duct Leakage) • Wireless HVAC Sensors • Photosensor-based Lighting Control
Demonstration and Evaluation	• Wireless HVAC Sensors and Controls • Optimal Whole Building Control Systems • Packaged RTU AFDD • Automated Whole Building Diagnostics
Market Promotion / Deployment	• Commissioning • Dampers AFDD • Occupancy Sensors • Packaged RTU AFDD

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Appendix A – Common Control Components, Building Systems, and Building Equipment

A.1 **Control Components**

Control components, such as sensors, controlled devices, and controllers, are essential to controls implementation. The following sections explain the different control components in greater detail.

A.1.1 Sensors

Sensors measure a physical quality of an environment and transduce the measurement into a mechanical (e.g., pneumatic) or electronic signal. In turn, the controller interprets the sensor signal and integrates the measurement into the control loop. Table A-1 lists several different types of sensors that interface with building controls. Temperature sensors account for the vast majority (about 75%) of building controls sensors sold (BCS 2002).

Table A-1: Types of Building Control Sensors

Sensed Variable	Types
Temperature	Bimetal element, rod-and-tube element, thermocouple, thermistor, infrared
Fluid Flow	Orifice plate, pitot tube, venturi, turbine, magnetic flow, thermal
Humidity	Mechanical hygrometer, electrical hygrometer, infrared hygrometer
Pressure (and differential pressure)	Diaphragm, Bourdon tube
Light Intensity	Photosensor
Occupancy	Infra-red, ultrasonic, CO_2*
*CO_2 is used as a *proxy* for occupancy but does not measure actual occupancy.	

Figure A-1 shows several temperature sensors used in HVAC applications.

Figure A-1: RTD Duct Temperature Sensors (left) and Electropneumatic Pressure Sensors (right) (Sources: Mamac)

Sensors typically communicate information to controllers in pneumatic, resistance, or electronic (analog) formats. Most new sensors are electrical and provide either current- or voltage-based signals, such as 4-20mA (most common), 0-20mA, 0-10V DC, or 0-5V DC. Sensors with digital outputs, e.g., via serial communication of the temperature, also exist (DDC Online 2004).

To be effective, sensors must provide a tangible change in its output signal over the expected measurement range. In some control applications, the controlled variable must remain within a narrow band around a desired set point and the sensor must have sufficient accuracy to enable tight control. Furthermore, the sensor response time must be significantly shorter than the controlled system time constant and the time change of process disturbances to maintain control of the system. The time constants of most HVAC applications tend to be relatively long (ASHRAE 2001; Sellers 2003b).

Sensor accuracy is important for maximizing the performance of commercial building HVAC systems. Sensor inaccuracy can manifest itself in many ways, including, for example, initial calibration errors, errors that vary based on whether reading nearer to zero or nearer to full scale, and long term drift errors (Hagen 1998). Manufacturers' published sensor accuracy figures often lump together several different types of inaccuracies, such as those listed above and, in addition, hysteresis, linearity, repeatability and interchangeability. Poor installation practices are also responsible for inaccuracies, and these can be far more significant than those intrinsic to the sensor. Section 9.5 discusses the accuracy of common sensor types.

A.1.2 Controlled Devices

Controlled devices regulate the flow of the control agent in a building system. Water and steam flow valves and airflow dampers are commonplace examples (see Figure A-2).

Figure A-2: A Control Damper and Damper Actuator (Sources: Ruskin and Neptronic)

An actuator provides the control link between the control signal and controlled device, translating the signal into a change in the controlled device position. Actuators can use pneumatic, electric, or hydraulic energy to power the motion of the valve stem or damper linkage through its operating range. For example, a pneumatic valve actuator is a springopposed, flexible diaphragm attached to the valve stem that adjusts the valve position via a change in the differential pressure across the diaphragm (see Figure A-3).

Figure A-3: Ball Valve (left) and Pneumatic Actuator (right) (Sources: Siemens and Masoneilan Dresser)

By contrast, an electric valve actuator relies upon a motor to move the valve stem via a gear train and linkages. Other examples of controlled devices include pumps, fans, compressors, solenoid valves, and lights.

A.1.3 Controllers

A controller receives information about the control variable and other relevant parameters from a sensor(s), compares the value with the desired control variable set point, and determines an appropriate output signal to the controlled device. Both hardware and software controllers exist. Many different types of controllers exist, particularly within the category of hardware-based controllers. Hardware-based controllers are analog device that continuously receive and act on data. Bimetal element thermostats, humidistats, electric resistance-based valve modulation, and electromechanical light switches are examples of hardware controllers. Software-based controller, in contrast, acquires data at discrete intervals (sampling) in a digital format and uses a microprocessor-based software program to determine the appropriate control action. Many controllers are not designed to turn on and off devices that have larger electric loads, such as compressors, pumps, or larger fans. Instead, the controller sends a signal to an electric relay that directly controls the flow of electricity to the controlled device (ASHRAE 2001).

Controllers can receive inputs and produce outputs in several formats, including (but not limited to) pneumatic, electronic, and digital. The communication format does not, however, explicitly determine the type of controlled device, i.e., a digital controller can control a pneumatic valve actuator. Pneumatic receiver-controllers are usually combined with pneumatic elements that mechanically react to the sensed variable to obtain a variable output air pressure. Electronic controllers receive an analog electronic signal from the sensor (such as 4-20mA or 0-10V), compare it with the set point, and then send out an analog electronic signal to regulate the controlled device. Digital controllers convert the electronic signals to numeric values and feed these values to a microprocessor that executes control algorithms on one or multiple control loops. Digital controllers fundamentally differ from pneumatic, electromechanical, and electronic controllers in that the control algorithm resides in memory as a set of program instructions. The digital controller calculates the control signals digitally rather than using an analog circuit, as in electric controllers, or mechanical change, as in pneumatic controllers. Digital controllers also use a control loop much more efficiently than pneumatic or electro-mechanical control methods. Because of the controller's operating speed, it can sample multiple sensor devices in milliseconds, which enables it to simultaneously control many control loops. Table A-2 describes the pros and cons of the three main types of controllers. Many control systems use a combination of controllers and are called hybrid systems.

Table A-2: Common Controller Types and Their Pros and Cons (based on ASHRAE 2001 and Other Sources)

Controller Type	Pros	Cons
Pneumatic Receiver	• Pneumatic valve and actuator dampers are inexpensive, reliable, and inherently modulating • Easy to maintain	• Requires compressed air service and very clean air supply • Imprecise • Leaks in the air system • Requires periodic calibration
Electronic (analog)	• Signals flow more quickly than pneumatic control signals • Accurate, free of drift, and inexpensive • Easy to implement PI control	• More expensive than pneumatic • Different types of systems used making interchangeability difficult • Require periodic calibration
Digital	• Very flexible and precise • Complete absence of drift • No calibration required • Can retrofit analog systems to digital	• Different programming languages used makes commissioning and maintenance difficult • User interface often not user friendly • Usually more expensive • Often perceived as more difficult to maintain[205]

Although the building controls market has moved away from pneumatic controllers towards analog and ultimately digital controllers, some issues remain with digital controls. Digital controllers can be furnished with both preprogrammed firmware and user-programmed logic routines. Preprogrammed logic control routines, known as firmware, are typically stored in permanent memory. Parameters such as set point, limits, and minimum off times within the control routines can be modified by the operator. However, the operator cannot change the underlying program logic without replacing the memory chips. User-programmable logic controllers allow the user to alter the algorithms. Routines for timers,

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[205] Sellers (2003a) notes that maintenance personnel often perceive electronic controls as more complex and intimidating than mechanical controls.

Boolean logic, modulating control and standard energy management routines may be preprogrammed and may interact with other control loops.

In many instances, practical considerations limit the performance gains possible from DDC. Although DDC controllers can rapidly process information to make control decisions, the slow response of electric actuators can often compromise the effective response speed. For instance, pneumatic valve actuators can move the valve stem through its full range of motion much more quickly than electric actuators, e.g., in 1 or 2 seconds versus at least 30[206] (Sellers 2003a). In other cases, the slower response times of mechanical sensors effectively damps and filters sensor input, which isolates the controller from reacting to transient signals. This can reduce or even eliminate cycling due to fluctuations in a controlled variable and improve control stability.

Figure A-4 presents an electronic controller and actuator for a VAV box.

Figure A-4: Variable Air Volume (VAV) Terminal Unit Controller and Actuator (Source: Amerilon)

Centralized control systems have both *primary* and *secondary controllers*. As their name implies, primary controllers provide higher-level control and typically have more communication and control capabilities than secondary controllers (see Table A-3). Whereas a primary controller usually controls many devices, a secondary (or terminal) controller often controls a single VAV terminal unit, fan-coil unit, or simpler air-handling units (Santos and Rutt 2001).

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[206] Shorter electric actuator times are possible but generally cost-prohibitive.

Table A-3: DDC Primary and Secondary Controller Features (based on DDC Online 2003)

Type of Controller	Characteristics
Primary	• Real-time (and accurate) Clock Function • Full software complement • Supports global control strategies • Buffer for alarms, messages, trend and runtime data • Freeform programming • Downloadable database • Higher analog-to-digital conversion resolution
Secondary	• Do not necessarily operate alone • Limited software complement • Usually do not store trend data • Freeform or application-specific software • Lower analog-to-digital conversion resolution

A database[207] maintained by the National Building Controls Information Program (NBCIP) provides a wide range of information about different DDC control products manufactured by different vendors.

A.1.4 Thermostats

A thermostat incorporates both an element that reflects the surrounding temperature[208] and a controller. Figure A-5 shows images of different thermostats.

Figure A-5: Three Thermostats (Source: Honeywell)

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[207] Information available at: http://www.ddc-online.org/manufacturers/index.html .

[208] Although all thermostats have an element that changes with temperature, thermostats may or may not have a sensor that measures and produces a signal that reflects the temperature. For example, a digital thermostat has a temperature sensor (e.g., thermistor), whereas a thermostat with a bimetallic element that expands and contracts with temperature and turns on or off space conditioning.

Table A-4 lists some of the different types of thermostats and their pros and cons. Digital thermostats have many of the same features.

Table A-4: Types of Thermostats and Their Pros and Cons (based on ASHRAE 2001)

Type of Thermostat	Functionality	Pros and Cons
Electromechanical	Employs movable tabs to set a rotary timer and sliding levers for day and night temperature settings	*Pros*: Inexpensive, easy to use, best for people with regular schedules *Cons*: Limited flexibility
Digital	Provides precise temperature control and custom scheduling	*Pros*: Many features, high flexibility *Cons*: Programming can be complicated
Occupancy or dual-temperature	Maintains a setback temperature until heating/cooling is called for manually	*Pros*: Easy to use, best for spaces that are mostly unoccupied *Cons*: Limited flexibility
Light Sensing	Uses lighting level preset by owner to activate heating systems	*Pros*: No battery required, no programming required, reset after power failures *Cons*: Heating depends on lighting level
Submaster	Changes set point in response to output from a master controller, usually another thermostat, manual switch, or pressure controller	*Pros*: Enables multizone control *Cons*: No control at the zone level

Electromechanical thermostats are the most common, least expensive and easiest to use of the thermostats available. However, the market is moving toward the more complex digital and submaster thermostats capable of accommodating particular zone needs and schedules.

A.2 Common Energy-Consuming Building Systems and Their Control

A.2.1 Central Air Handling Systems / Air Distribution Systems

An HVAC system is generally a combination of a primary system and a secondary system. The primary system converts energy from fuel or electricity into thermal (heating or cooling) energy, while the secondary system delivers heating, ventilation, and/or cooling to the conditioned space. The basic secondary system is an all-air, single-zone, air-conditioning system consisting of an air-handling unit (AHU) and an air distribution system. Figure A-6 presents a central AHU.

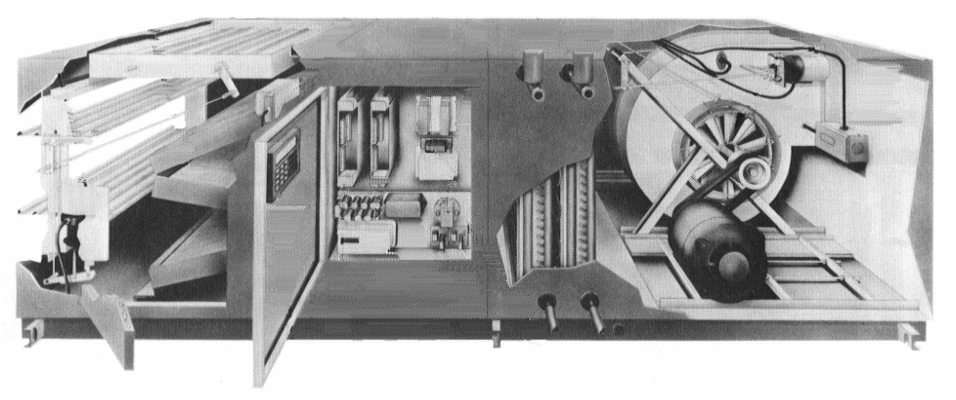

Figure A-6: A Central System Air-Handling Unit (from ADL 1999; Source: Carrier)

HVAC systems can be central or decentralized. In a central system, air and/or water distribution systems distribute ventilation, heating and cooling to the rest of the building from primary equipment located in a central plant, e.g., a central air conditioning system with associated water chiller(s) and boiler(s). In contrast, a decentralized system has primary equipment located in several different locations throughout, on, or adjacent to the building. A room air conditioner is an example of decentralized equipment. Figure A-7 depicts a central air system that works in conjunction with chilled and hot water systems.

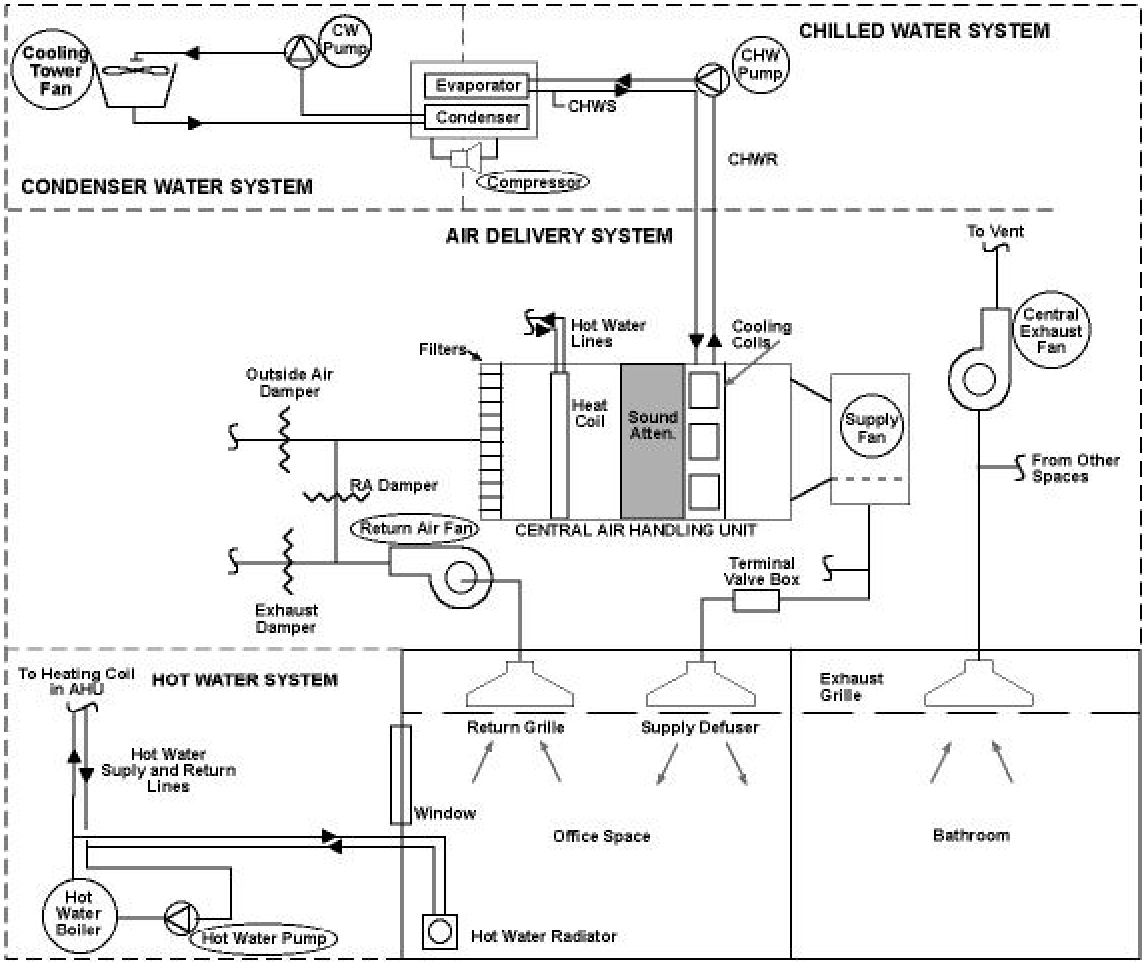

Figure A-7: Schematic of a Central System (from ADL 1999)

An all-air system provides heating, humidification, and cooling by supplying conditioned air to the conditioned space without additional space conditioning at the zone level. Many buildings that require individual control of conditions and having a multiplicity of zones use all-air systems, such as: office buildings, schools and universities, laboratories, hospitals, retail stores, hotels and ships. All-air systems also serve special applications that require close control of temperature and humidity, such as clean rooms, computer rooms, hospital operating rooms, and textile and tobacco factories. The system may provide heating through the same duct system used for cooling, from a separate perimeter air system, or from a separate perimeter baseboard system using hot water, steam, or electric-resistance heat. Cost plays a major role in the decision to install a central all-air system into a new building. Older buildings generally do not employ a central all-air system because they lack ductwork or the space to install ductwork.

All -air systems are classified as single-duct systems and dual-duct systems. Single-duct systems contain the main heating and cooling coils in series in the airflow path. A common duct distribution system at a common air temperature feeds all conditioned spaces. Single-duct systems can vary either the air temperature or the air volume to provide the needed space conditioning to each zone. Dual-duct systems contain the main heating and cooling coils in either a parallel flow or series-parallel flow air path. Separate cold and warm air ducts distribute the air and blend it at the conditioned space. Dual-duct systems can vary the volume of supply air in some applications. However, they more often vary the supply air temperature by mixing two air streams of different temperatures. In general, design practice has moved away from dual-duct systems due to their cost and relative inefficiency.

Single-duct and dual-duct systems can be further classified as constant air volume (CAV) or variable air volume (VAV) systems. CAV systems maintain constant airflow levels while changing the supply air temperature to condition the space. In contrast, VAV systems control temperature in the conditioned space by varying the volume of supply air rather than changing the supply air temperature.

Figure A-7 presents a basic single-duct, CAV system. The system circulates a constant volume of air through the building, with a fraction of the air taken from outside and, under many conditions, the rest from the conditioned space through a return air system. Given the building conditions, the system controller applies a predetermined control strategy for the building condition to determine the target air temperature and flow and sends signals to the three dampers to provide the desired air mix. When the temperature (or enthalpy) of the outdoor air (OA) falls below that of the return air (RA), it can be more economical to increase the OA fraction to cool the building rather than circulate return air, i.e., economizing. After passing through the dampers, the air passes through filters and the heating or cooling coil condition the air to the desired air supply temperature and appropriate humidity level. Finally, the conditioned air passes through the ductwork and diffusers to the conditioned space. In each zone, a thermostat maintain the desired temperatures by adding varying quantities of heat (reheat) to modulate the air temperature supplied to each zone based on feedback from thermostats.

Several economizer control strategies exist, all of which vary OA air fraction (and OA damper position) as a function of OA enthalpy or temperature (see Table A-5). A recent study of 123 smaller packaged rooftop units with economizers serving *newly-constructed* commercial buildings in California found that differential enthalpy was the most common (40%) control strategy, followed by high limit dry bulb temperature (23%), high-limit enthalpy (21%), and differential temperature (16%) strategies (Architectural Energy 2003). It is not clear how these findings apply to other parts of the country or the existing building stock in California.

Table A-5: Economizer Control Strategies

Economizing Strategy	How It Works
Differential Dry Bulb Temperature	OA damper goes to 100% OA when the difference between the OA and RA temperatures exceeds a threshold (e.g., based on typical OA moisture content for a climate)
Differential Enthalpy	OA damper goes to 100% OA when the difference between the OA and RA enthalpies exceeds a threshold
High Limit Dry Bulb Temperature	OA damper goes to 100% OA when the OA temperature falls below a threshold (e.g., based on typical OA moisture content for a climate)
High Limit Enthalpy	OA damper goes to 100% OA when the OA enthalpy falls below a threshold
Non-Integrated Economizer Controlled by Two-Stage Thermostat	The first stage opens the economizer, and the second stage locks out the economizer and begins mechanical cooling (Katipamula et al. 1999, PECI 2003).

Figure A-8 illustrates how the OA fraction can vary as a function of OA temperature for an AHU with economizer functionality. Other AHU economizers may have a simple on-off functionality, i.e., providing full OA or minimum instead of varying OA fraction over its full range. Above the threshold (determined for each strategy and climate), the OA damper provides the minimum quantity of OA while the cooling system provides cooling. When the OA temperature or enthalpy falls below the threshold, the economizer provides 100% OA to provide the maximum cooling effect and the cooling system continues to provide additional cooling to mitigate internal and shell loads. At a somewhat lower OA temperature, the OA can meet all of the (typically decreasing) internal and shell loads and the cooling system turns off. As the OA temperature decreases further, the cooling loads decrease and the cooling effect of the cooler OA increases (due to lower OA temperature), so the economizer OA intake also decreases. At some cooler temperature, the minimum OA fraction balances the internal loads and space heating begins.

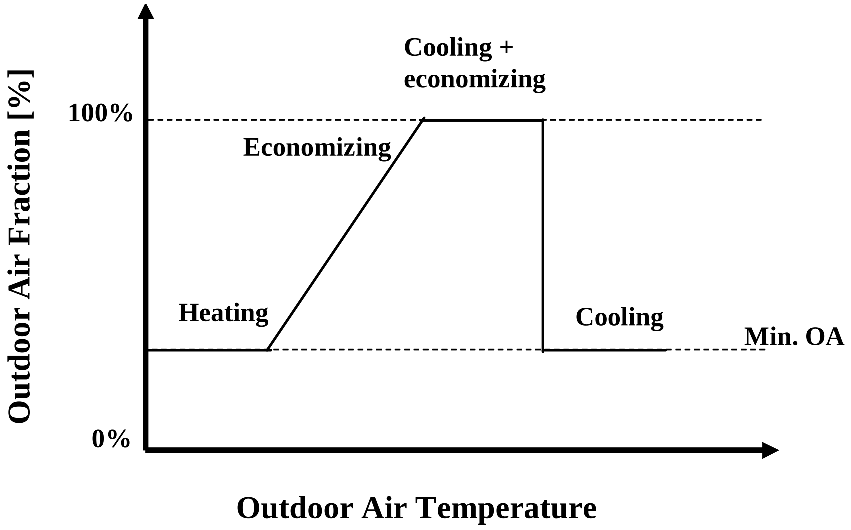

Figure A-8: Simplified Overview of AHU Outdoor Air Fraction Function (based on Katipamula et al. 2003)

All-air systems can accommodate multiple zones as well. The multizone central all-air system provides a single supply duct for each zone and obtains zone control by mixing hot or cold air at the central air handling unit in response to room or zone thermostats. Single-zone ducts distribute mixed, conditioned air throughout the building. Multizone systems can be either CAV or VAV. Multizone and dual duct systems both mix hot and cold air, multizone systems within the central equipment and dual duct systems at each space served. For a comparable number of zones, the multizone system provides greater flexibility than the single duct system and costs less than the dual-duct system. On the other hand, each central unit can serve a limited number of zones, usually about 12 zones (ASHRAE 2001).

The reheat systems are a variant of the single-duct CAV system that applies heat to either preconditioned primary air or recirculated room air. Regardless of the load, the central unit supplies primary air at a constant temperature, i.e., 55°F. The reheat system adds heat to the air stream at each zone to match the cooling capacity to the current load in that zone. This increases both cooling and heating energy consumption. However, the supply air temperature from the central unit can be varied, with proper control, to reduce the amount of reheat required and the associated energy impact. Despite increased energy consumption, reheat can improve comfort by: 1) heating uncomfortably cool dehumidified air to an acceptable temperature; 2) zone control for areas of unequal loading, such as heating/cooling of perimeter areas with different sun exposures; and 3) close control of zone conditions for process of comfort applications.

Larger new buildings typically have VAV central systems that deliver air from central air handling units (often with variable-speed drives) to each zone via terminal units (also known as VAV boxes) and, ultimately, diffusers (see Figure A-9).

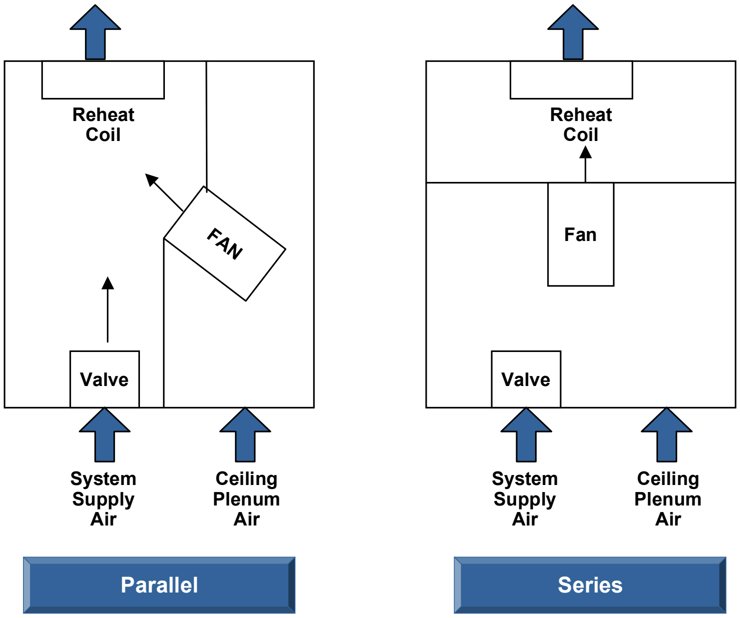

Figure A-9: Parallel and Series VAV Boxes (from ADL 1999)

Each VAV box modulates its damper position to control the airflow to and temperature in each zone. The following control strategy is typical for VAV central systems fed by chillers.

- A thermostat in each zone senses the local temperature and calls for cooling;
- In response, the local VAV box controller adjusts the box's damper position to change the amount of cold air flowing to the zone;
- The supply air fans for each VAV box modulate to maintain a specified duct air pressure to ensure proper box operation;
- In response to the net change in system airflow, the central AHU controller modulates supply and return airflow to maintain proper function of all VAV boxes;
- Typically, the VAV central AHU delivers air at a constant temperature to the zones. Changes in the airflow and cooling demand at VAV boxes causes the central controls to modulate the cooling delivered to the AHU coils.

System set points can be optimized to achieve optimal system control, which can potentially be implemented on both existing and new systems. Systems with modern, computerized control systems can achieve energy savings with little or no capital expenditure (JCEM 1998). In practice, however, system set points usually are not optimized to minimize energy use (ASHRAE 2001).

A.2.2 Hydronic and Steam Systems

Hydronic systems distribute hot or cold liquid water to central station air handling units or directly to conditioned spaces to meet heating and cooling loads. A boiler (or chiller) heats (cools) the water and (typically) a pump distributes the water through a dedicated piping distribution system to heat transfer units, e.g., radiators and fan coil units, located centrally or distributed throughout the conditioned space. Subsequently, the heat transfer units deliver the heating or cooling to the specified spaces (see Figure A-10).

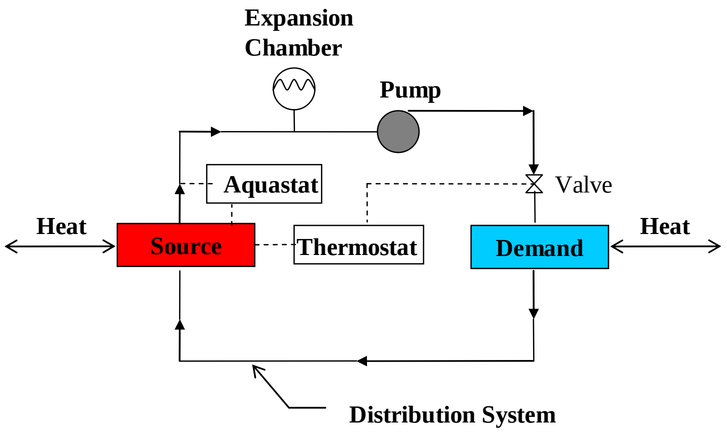

Figure A-10: Schematic of Basic Closed Hydronic System (based on ASHRAE 2000)

The *source*, e.g., a boiler or chiller, generates the hot or cold water used to meet the design loads (see Table A-6) and the *demand* transfers heat between the conditioned space and the hydronic distribution system. Common examples of hydronic demand devices include radiator and fan coil units. Most demand devices are water-to-air finned coil heat exchangers.

Table A-6: Hydronic System Demand and Source Devices (based on ASHRAE 2000)

Function	Common Demand Devices	Common Source Devices
Heating	Preheat coils in central units Heating coils in central units Zone or central reheat coils Finned-tube radiators Baseboard radiators Fan-coil units Radiant heating panels	Boiler Heat pump
Cooling	Coils in central units Fan-coil units Induction unit coils Radiant cooling panels	Chillers Heat pump

Closed water loop heat pump systems (sometimes referred to as California heat pumps) serve a limited number of buildings in moderate climates. The closed water loop circulates

60 to 90°F water throughout the building and transfers heat from warmer to cooler portions of the building.

Pumps, typically centrifugal pumps, drive the water flow through hydronic systems. Variable-flow chilled-water systems typically use either a primary-only or primary-secondary configuration (see Figure A-11).

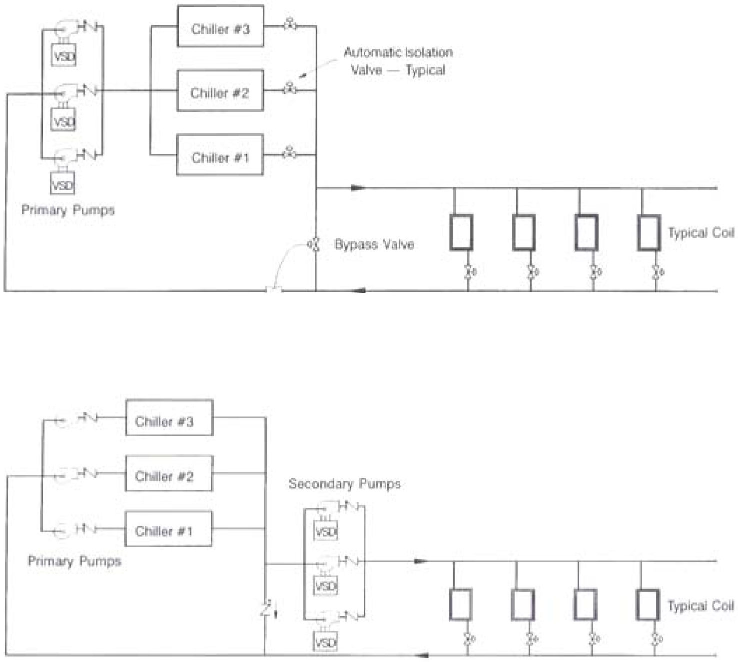

Figure A-11: Primary-Only (top) and Primary-Secondary (bottom) Chilled Water Loops (from Taylor 2002)

Primary-only systems have one or more variable-speed primary pumps provide flow to the chillers, from which chilled water flows through cooling coils and/or a bypass. The VSDs modulate the pumps' speeds and control the flow through the bypass valve to deliver the desired amount of cooling to different zones while ensuring that all chillers receive their minimum flow volumes. When building loads reach the point where another chiller needs to come on line, the chiller control system unloads the operating chiller(s) and gradually increases the flow through the "new" chiller. This avoids a precipitous drop in chiller flow, which could trip off the affected chiller(s). Subsequently, the control system coordinates the ramp up of chiller outputs and water flow rates to satisfy the increased building loads. Primary-secondary systems, in contrast, have single-speed primary pumps that feed the chillers, with secondary pumps downstream of the chillers that vary the flow to the coils. Primary-only systems have a lower first cost and consume less energy than primary-secondary systems, but have control challenges. Notably, it can be difficult to effectively control the bypass flow to maintain minimum chiller flow in primary-only systems. Specifically, constant flow and primary-secondary loops used pressure-based activation to control bypass valve. This does not function effectively in a system with variable-flow primary pumps, however, because variable-speed pumping reduces the pressure at the bypass valve. It can be challenging to develop a control scheme that effectively and robustly manages bypass flow rates over a wide range of operating conditions, particularly in systems that have chillers of several different capacities. In addition, attention needs to be paid to the control procedure to coordinate the operation of multiple chillers when bringing an additional chiller on-line in a primary-only arrangement because start-up of a new chiller can temporarily reduce the flow through the operating chillers and cause the chillers to trip off (from insufficient flow; Taylor 2002).

Systems with multiple pumps also require an understanding of the combined pump operation in either series or parallel to avoid system performance problems. For example, a system with pumps of different flow capacities operating in series must avoid "overflowing" the pump(s) of lesser capacity to avoid cavitation. In a system with parallel pumps, if pumps develop unequal head, one pump may cause the pressure across a second pump to exceed its cutoff pressure, diminishing or stopping flow through the second pump.

The piping distribution system connects the different system components. During piping system design, the designer needs to ensure that the piping-pump combination can meet the design heating and cooling loads by having sufficient flow capacity given the piping layout (and associated flow resistance). Two general types of load distribution circuits exist: series and parallel. Hydronic systems tend to use parallel piping circuits because they provide the same temperature water to all portions of the distribution system.

Dual-temperature systems are used when the demand devices and distribution systems provide for both heating and cooling. They come in three basic configurations: 1) two-pipe systems; 2) four-pipe common demand device systems; and 3) four-pipe independent demand device systems.

In a two-pipe system, the demand devices and the distribution system circulate chilled water when cooling is required and hot water when heating is required. Conditioned water flows from the source to the demand device through one pipe and returns back through the second pipe. Since the same demand devices and distribution system provide both heating and cooling, the system can only operate in one mode at a time and require seasonal changeovers between heating and cooling modes. In a four-pipe common demand device system, the demand devices are used for both heating and cooling, as in a two-pipe system. However, the changeover from one mode to the other takes place at each individual demand device, rather than for the entire system. A four-pipe independent demand device system is essentially two independent hydronic circuits, one for heating and another for cooling. Therefore, some demand devices can be in the heating mode while the others can be in the cooling mode. Table A-7 summarizes the pros and cons of the different systems.

Table A-7: Pros and Cons of Different Types of Dual-Temperature Systems (based on ASHRAE 2000)

Dual-Temperature System	**Pros**	**Cons**
Two-Pipe	• Least costly	• All demand devices must require heating/cooling at the same time • Changeover from heating/cooling to cooling/heating requires considerable time, otherwise damage may occur in chiller/boiler • Not appropriate if rapid swings in load are anticipated
Four-Pipe Common Demand Device	• Changeover from heating / cooling to cooling / heating takes place at each individual demand device	• Potential mixing of hot and chilled water at each demand device connection • Demand devices usually do not have individual heating / cooling capacity control
Four-Pipe Independent Demand Device	• Simpler and more reliable control than four-pipe common demand device system • Demand devices have individual capacity and flow control • Offers additional flexibility when some demand devices are for heating or cooling only, such as unit heaters	• Most expensive of the three types

Hydronic system control can be achieved by on-off control and modulating control. In general, on-off control is generally limited to smaller systems (e.g. residential or small commercial) and individual components of larger systems. In smaller systems where the building is a single zone, a thermostat controls the cycling of the source device (the boiler or chiller) on and off. Modulating control typically allows the chiller or boiler to run while a water temperature thermostat (aquastat) modulates the chiller or boiler output as a function of either the supply or return water temperature. The hydronic pump can either cycle with the demand device, as is usually the case in residential heating, or run continuously, as is usually done in commercial water systems.

Control valves control demand devices by varying the amount of water flow through the demand device. Control valves for hydronic systems are two-way or three-way valves. A two-way valve modulates the flow through the load in response to changes in sensed demand (via a thermostat). The valve modulates system flow in response to demand, which allows reductions in pumping power at part-load conditions. In contrast, a three-way valve maintains a constant system flow but bypasses a portion of the system flow around the load and varies the degree of bypass in response to constant flow response.

Steam systems supply heat by generating water vapor and distributing the vapor to deliver heat. Steam systems have several advantages over hydronic systems. Steam flows through the system unaided by external energy sources such as pumps[209], reducing the energy consumed to distribute the heat. In addition, the lower density of steam (relative to liquid water) favors the use of steam systems in tall buildings where hydronic systems create very high head pressures for pumps. Steam system components can be repaired or replaced by shutting off the steam supply and allowing the remaining liquid to drain off. In contrast, water system repairs require draining and subsequent refilling after completion of the repair. Finally, because of the large latent heat of steam, steam systems usually experience little change in temperature throughout the distribution system.

The main disadvantages of steam systems arise due to the presence of both liquid and vapor in the system. If the condensate (condensed steam) does not drain properly from pipes and coils, the rapidly flowing steam can push a slug of condensate through the system. This can cause water hammer and result in objectionable noise and, in more extreme cases, damage to piping and system components. The presence of air in steam systems reduces the steam temperature as well as reducing the heat transfer capability of demand devices by insulating internal heat transfer surfaces. Oxygen in the system causes pitting of iron and steel surfaces. Furthermore, any carbon dioxide in the steam dissolves in condensate and forms carbonic acid, which is very corrosive to pipes and equipment. In some cases, steam traps, devices installed to remove condensate from steam distributions systems, can leak and lead to high levels of energy waste (as discussed in Section 8.12, "Valve Leakage”).

Steam and hydronic systems share the same basic components, with the exception that steam systems do not have an expansion chamber or pumps and have a single pipe carrying steam to (and condensate back from) radiators. Steam heating systems control heat output by changing the steam temperature exiting the boiler or by modulating a valve to vary the amount of steam delivered to individual zones. Some systems combine the two control approaches to enhance control and operating efficiency (ASHRAE 2001). A facility’s boiler or a central utility, i.e., district heating, can provide steam. Central utilities often do not accept condensate, in which case the using facility discharges the condensate and often loses the associated sensible heat (equal to ~10 to 15% of the purchased heat; ASHRAE 2000).

Due to first cost, maintenance, and water management/leakage issues, new commercial buildings are more likely to have central air systems instead of hydronic and steam systems.

A.2.3 Lighting Controls

Electronic lighting controls control lighting levels for aesthetic, security, or energy management purposes. Aesthetic control adjusts lighting intensity for the application and controls the quality and feel (ambiance) of the visual environment, for example, dimmable lights in a concert hall or a restaurant, or bright lighting in a retail establishment to draw attention to clothing or jewelry and enhance its attractiveness. Lighting controls can also enhance security, for instance, lighting walkways at night or automatically turning on lights

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[209] Steam systems do require boiler feed water pumps.

in response to triggering of an alarm system. Lighting control for energy management control limits the time and/or intensity of lighting in response to the time of day or ambient light levels to reduce unneeded lighting. Historically, lighting controls were primarily used to turn lights on and off, or for special purposes such as stage, theater, and conference room lighting. More recently, lighting controls have become an integral element of good lighting design and an important part of energy management programs for lighting.

Control systems vary greatly in degree of automation, ranging from manual (wall switches) to highly automated. Automatic controls can reduce energy consumption but are not always the most effective in terms of cost and occupant response. All lighting control systems contain four major components: a sensing device, a logic circuit, a power controller, and light sources (see Figure A-12).

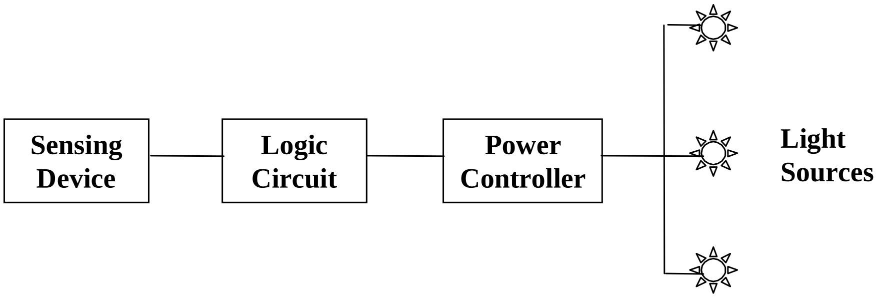

Figure A-12: Diagram of a Basic Lighting Control System

The wiring system links these components to each other, except in the case of wireless control systems where radio and/or infrared signals control the light sources. The sensing device, such as a photosensor, occupancy/motion sensor, or a timing device, assesses the current conditions and sends a signal reflecting those conditions to the logic circuit. The logic circuit accepts the signal from the sensing device and, based on preprogrammed logic, determines when to supply light and, in some instances, how much light to supply. In turn, the power controller, such as a dimmer, relay, or switch, accepts the signal from the logic device and alters the output of the light sources. Figure A-13 depicts a basic central lighting control system.

Figure A-13: Interior of a Lighting Control Panel (Source: Watt Stopper)

Building lighting controls can function at either a central or localized level, or some combination of the two. A localized lighting system consists of independently controllable zones. Sensor outputs only directly influence the local lighting; thus, each zone operates independently of other zones. In contrast, central systems generally control multiple zones, usually as part of an Energy Management Control System (EMCS). Most conventional central lighting systems have a central lighting controller that switches relays for a group of lights in response to inputs (i.e., central workstation, photocells, occupancy sensors, etc.). Alternatively, central systems may also control individual lamp ballasts via low-voltage (0 to 10V) signals from the lighting controller to each light. Although these systems can offer centralized lighting control, the need for dedicated relays or lighting control wiring makes centralized control based on local lighting needs complex and expensive (see, for example, Treado 2004).

Several control strategies exist, including:

- Predictable scheduling;
- Occupancy-based control;
- Daylighting & Lumen maintenance;
- Bi-level switching; and
- Aesthetic controls.

Predictable scheduling turns on and off luminaires based on a fixed schedule to avoid lighting when the building or space is unoccupied. It applies primarily to buildings and spaces with regular, predictable schedules, for instance, office buildings based on staff arrival and departure times, cleaning staff hours and over weekends and holidays. EMCS, lighting automation panels, and time clocks (mechanical, electrical or digital devices that control lighting panels based on time of day schedules determined by the building operator) are usually used to implement automated scheduling of lighting control. Predictable scheduling strategies using timing devices can reduce energy consumption by up to 40% by eliminating energy waste caused by lighting unoccupied spaces (IESNA 2000). A recent survey of commercial building renovation and new construction projects in California found that approximately 40% and 50%[210], respectively, installed automated lighting scheduling (DiLouie 2003a).

Occupancy-based control uses occupancy or motion sensors to sense the presence of people in a space. If the sensor determines that the room is occupied, the controls activate the luminaire(s); otherwise, the luminaire(s) remains off. This strategy realizes the greatest savings in spaces with sporadic and lower rates of occupancy, such as conference rooms, restrooms, filing areas, break rooms, etc. The most common occupancy sensor types are infra-red and ultrasonic, and the sensors typically include a timer to leave the lights on when people are in a room but are not moving (ultrasonic) or have entered a "dead zone" (infra-red).

Figure A-14: A Passive Infra-Red (left) and Dual Technology (PIR+Ultrasonic; right) Occupancy Sensors (Sources: Lighting Design Lab and Watt Stopper)

Both types of sensors can operate either independently or with an EMCS; in some cases, they can also feedback to HVAC systems to modify space temperature set points, e.g., for hotel or conference rooms. In some private offices, workers overrode occupancy sensors because they want their lights to remain on to signify that they were at work (Diamond and Moezzi 2002). The energy savings potential of occupancy sensors depends highly on the type of building, the occupancy rates in a space, and the placement of the sensors in a room. The 1995 CBECS data also suggest that occupancy sensors served about 6 billion ft^2 of floorspace – about 10% of all commercial building floorspace[211], presumably integrated with lighting controls. Recent survey data suggest that occupancy sensor usage has surged in the past few years, with approximately 60% to 70% of all commercial building new construction and renovation projects in the state of California incorporating occupancy sensing (DiLouie 2003a). It is not clear, however, the extent to which this trend applies to

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[210] New construction had a range of 48% to 58% depending on building type, while retrofit construction ranged from 35% to 58%.

[211] 1995 data were used because the 1999 survey did not cover occupancy sensors; BOMA (2000) found a similar market penetration in their survey of commercial building owners. Occupancy sensors integrated with lighting controls have much higher market share in California; see RLW (1999) for additional information about occupancy and daylight sensors applied to lighting.

the rest of the U.S., as California has a history of aggressively adopting energy efficiency measures relative to the country as a whole. Section 9.6 discusses occupancy sensors in greater detail.

Daylighting employs photosensors, switches and dimmers to reduce or turn off the lighting in areas that have sufficient illumination from daylight (see Figure A-15).

Figure A-15: Photosensor and Controller (Source: Intelligent Lighting Controls)

This strategy primarily applies to perimeter areas of buildings, where sunlight can provide all or a significant part of the desired illumination. In daylit spaces, illumination sensors measure the total amount of light in a space (both artificial and natural) and the controller use this information to dim (or turn off) the artificial lights to maintain design lighting levels. Incandescent light bulbs can operate with dimmers, while fluorescent lamps require dimming ballasts for effective dimming. Although illumination sensors for lighting control have been on the market for at least ten years (NEMA 1992), to date they have attained relatively little market penetration (PG&E 2000). A survey of new or renovated commercial buildings in California in the past few years showed a lower prevalence, on the order of 10%[212], of daylighting sensors than schedule- or occupancy-based lighting control (DiLouie 2003a). Many exterior lamps also use photosensors for on-off control. Section 9.9 discusses photosensor-based lighting control in further depth.

Lighting control integrate with illumination sensors also can reduce lighting loads by automatically dimming lights that produce excessive light for the task performed in a space or over-sized to compensate for lamp lumen depreciation (automatic tuning). The output of fluorescent lamps decreases as they age (lumen depreciation), in some cases by more than 20% (IESNA 2000). Lighting designers factor in lumen depreciation when they install lighting systems; thus, the lighting system initially puts out more light than needed. In other cases, spaces may be simply overlamped. The photosensor detects the actual illumination level and compares the illumination level to the target level. The lighting controls decrease

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[212] New construction had a range of 11% to 20%, retrofitted buildings a range of 8% to 20%.

the power flowing to the dimming ballast to reduce the illumination to the design level. In the case of lumen depreciation, the controls call for more power to maintain constant illumination as the lamp ages. The luminaire only draws full power toward the end of the lamp life.

Bi-level switching enables control of a light fixture to produce at least two different light levels. For instance, a luminaire containing two lamps could illuminate one or both of the lamps.

Aesthetic controls enable adjustment of space lighting to suit multiple purposes, to maintain visual performance, and to create or change the mood. Aesthetic controls include manual controls (switching and dimming), preset controls, and central dimming systems. Central dimming systems are the most powerful of the aesthetic control options. They have at least one control station that houses the control-function logic, processors, and several forms of manual controls, preset controls, and time-clock controls (IESNA 2000).

A.2.4 Water Heating Systems (Service Water Heating Systems)

Water heating systems, also known as service water heating systems, heat and distribute water to hot water terminal devices such as plumbing fixtures and dishwashers. A *heat energy source* (e.g., natural gas) provides the thermal energy to heat the water, the *heat transfer equipment* transfers the thermal energy to the water, and a *distribution system* distributes the hot water throughout the building to *terminal hot water usage devices* (see Figure A-16).

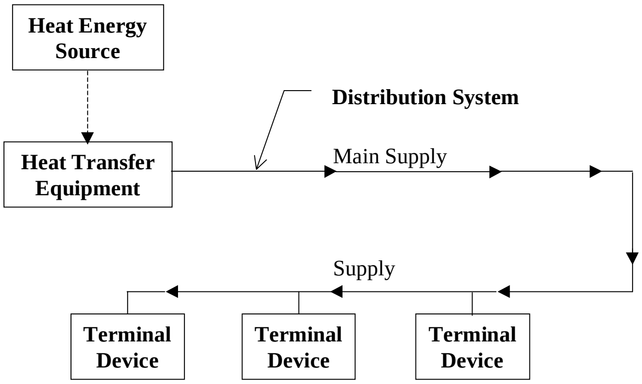

Figure A-16: Schematic of Basic Water Heating System (ASHRAE 1999)

The *heat transfer equipment*, transfers the heat from the heat energy source to the water. Most water heaters are an integrated combination of a heat energy source and the heat transfer equipment. Water heaters can be characterized as direct or burner indirect and as storage-water heaters or instantaneous water heaters. The direct type generates heat from either fuel combustion or electric heating and transfers the heat to the water within the water heater. Gas water heaters account for about 80% of water heaters installed in commercial buildings; most[213] other units are electric-resistance water heaters (ADL 2001b). In contrast, indirect water heaters utilize heat from remote heat sources, primarily boilers, but they can also take heat from solar energy collection, cogeneration, refrigeration, or waste heat. Storage tanks may be part of or associated with either type of water heater. Storage-water heaters allow use of a small heat input rate to serve hot water loads, which tend to have significant peaks in demand, while instantaneous water heaters require larger heat input rates to meet real-time water heating demands. Table A-8 outlines the pros and cons of the different types of water heaters commonly used in commercial applications.

Table A-8: Commercial Water Heater Characteristics (based on ASHRAE 1999)

Water Heater	Type	Pros	Cons
Storage Water Heaters	Direct (Gas & Electric)	• Incorporates burner/element, storage tank, outer jacket, insulation and controls in a single unit • Less expensive than instantaneous water heaters	• Standby heat loss when no hot water needed • Pilot light and flammable fuels pose dangers • Require storage tank space
Instantaneous Water Heaters	Direct & Indirect	• Provides a steady, continuous supply of water • Minimal standby heat loss	• Have minimal water storage capacity (flow rate limited by heating capacity) • Usually more expensive than storage water heaters

Most storage water heaters are heated by gas, electricity, or steam. In a gas storage water heater, the cold water feeds into the bottom of the tank and the heated water buoyantly rises to the top of the tank. Upon a "call" for hot water, water is drawn from the heated water at the top of the tank. When the water temperature falls below the minimum temperature set point (and the associated sensor deadband, usually about 5°F), a thermostat (aquastat) senses the low temperature and activates the gas burner at the bottom of the tank. The hot combustion gases transfer heat to the water through the burner housing and heat exchanger coil and exit the unit through the flue. An electric water heater works in much the same way as a gas water heater, except instead of a burner at the bottom of the tank, an electric water heater has two resistance heating elements. Steam-fired water heaters are usually indirect-fired devices with a heat exchanger that transfers heat from the steam (generated by a boiler) to the storage water heater The primary heating element is located at the bottom of the tank and the secondary element is located in the upper portion of the tank. A separate thermostat controls each heating element in the same way as a gas water heater thermostat. Typically, commercial building water heater set point temperatures range between 160°F and 180°F. Because storage water heaters maintain a volume of heated water at all times, they constantly lose heat to the surrounding environment (standby heat loss). To prevent

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[213] There are a limited number of direct oil-fired and heat pump water heaters.

catastrophic failure of the water heater tank, water heaters include temperature and pressure relief valves that open in case the water temperature approaches 210°F or the water pressure approaches the rupture pressure of the tank.

Instantaneous water heaters, also called tankless water heaters or demand water heaters, also primarily are heated by gas, steam, or electricity and have minimal storage capacity. When a hot water plumbing fixture turns on, a pressure sensor detects the pressure change and activates the burner/element. The water heats up as it flows through a coil heated by a gas burner or electric element. As soon as the hot water plumbing fixture turns off, the controls deactivate the burner/element. Therefore, instantaneous water heaters have minimal standby heat loss. Older instantaneous water heaters allowed the water temperature to vary depending on the volume of water use. In contrast, newer models have modulating gas valves or sequential electric elements that vary the amount of heat produced with the water flow rate to produce a consistent water temperature. Although an instantaneous water heater can provide hot water indefinitely, its heating capacity limits the maximum flow rate.

Other types of water heaters with much more limited market shares include heat pump and solar water heaters. Heat pump water heaters (HPWH) use a vapor-compression refrigeration cycle to extract energy from an air or water source. Most HPWHs are air-to-water units. They typically have a maximum output temperature of 140°F. HPWHs function most efficiently under conditions of low-temperature inlet water and hot and humid ambient air. Solar water heating systems collect energy from the sun to heat the water.

Hot water *distribution systems* transport the hot water from the water heating equipment to plumbing fixtures and other *terminal hot water usage devices* (e.g., dishwashers and washing machines). To prevent scalding at faucet fixtures, which can occur at water temperatures above 120°F, a mixing valve mixes the heated water with cold water to bring its temperature down. The building water service main replenishes water consumed by the water heater. In some locations, it is desirable to have hot water available continuously at fixtures, e.g., in hotels. These buildings use return piping systems that constantly circulate hot water to provide hot water without delay. Multistory buildings often use a booster pump to transport cold water to a higher floor, where it feeds the hot water system(s).

A.3 Common HVAC Equipment and Its Control

A.3.1 Boilers

Boilers produce heat (typically from combustion of gas, fuel oil, liquid propane, etc.) and transfer the heat to a fluid, usually water in liquid or steam form. A pump circulates the heated water or steam flows through pipes to heating coils or radiators, which warm the room air. The amount of heat in a zone can then be controlled be adjusting the flow of heated water in the radiators. The heating water or steam may also serve preheat coils in air-handling units and reheat coils. Boilers also generate hot water or steam for heating service water and other process needs. Some central systems have steam boilers rather than hot water boilers because of the need for steam conditioning needs (e.g., humidifiers in air-handling units) or process needs (sterilizers in hospitals, dry cleaning in laundries, etc.).

Boiler systems operate in response to primary and secondary controls. The primary control sensor in a system is usually a thermostat within the controlled zone that monitors the zone temperature. When the temperature falls below the set point, the thermostat actuates a valve supplying steam or hot water drawn from the boiler. As the steam or hot water leaves the boiler, the secondary control sensor activates the burner via ignition by a continuously burning standing gas pilot, an electric spark igniter, or a hot surface igniter. In mechanical draft combustors, activation of the burner simultaneously turns on a fan or blower to vent the combustion gases. The secondary control is located within the boiler and is usually a thermostat in a hot water system or a pressure sensor in a steam system. Both types of controls vary the fuel input to the boiler through a fuel valve; smaller boilers, however, tend to only have a single firing rates, i.e., to only operate in on/off mode.

Common examples of combustion fuel controls are *on-off, high-low-off*, and *modulating*. On-off control simply turns the burner on or off and does not control the rate of heat output from the boiler. High-low-off control starts the burner at less than full capacity (usually 60%) and then increases to full burning rate after several seconds. Modulating control regulates the burning rate to follow the load demands more closely than the on-off or high-low-off controls. The fuel control valve responds over a range of positions within the operating range of the burner. Modulating controls typically offer more precise water temperature control and higher efficiency than on-off or high-low-off controls. In addition, larger buildings may have several boilers capable of staged operation. Boiler sequencing controls determine which boilers to fire and the setting for each boiler based upon operational conditions (e.g., time of day, heating demand, boiler cycling frequencies) and reportedly can reduce boiler energy consumption by up to 7% (Showers and Lincicum 2003). In essence, this provides multi-stage control. Boiler controls also include safety features that shut off fuel flow when unsafe conditions develop (e.g., high boiler pressure).

A.3.2 Furnaces

Furnaces generate heat, usually from natural gas or electricity, and transfer it directly to air through heat exchangers. A typical furnace consists of a cabinet, heat exchangers, a combustion system including burners, a draft blower or draft hood for venting, a circulating air blower and motor, and an air filter. The blower draws air in through the air filter and circulates it over the heat exchanger. Ducts then distribute the heated air throughout the building.

Similar to boiler systems, furnace systems operate in response to primary and secondary controls. The primary control sensor in a system is usually a thermostat within the zone that monitors the zone temperature. Once the temperature in the zone drops below the set point, the thermostat activates the burner. The secondary control operates the circulating fan via a temperature-sensitive fan control switch exposed to the circulating air stream within the furnace cabinet or an electronically operated relay. In both cases, the controls delay start-up of the circulating fan by about one minute after start-up of the burners. This delay allows the heat exchangers time to warm up to eliminate the flow of cold air when the blower comes on. The controls also delay blower shutdown[214] for several minutes after the burner shuts down to extract residual heat from the heat exchangers (this improves annual efficiency).

A fuel valve controls the flow of fuel to the burner and has the same characteristics as boiler combustion controls, i.e. *on-off* control, *high-low-off* control, and *modulating* control. A temperature-sensitive limit switch exposed to the circulating air stream shuts off the fuel valve if the exit air temperature exceeds a predetermined threshold. This prevents overheating of the heat exchangers in case a severe reduction of circulating airflow occurs.

A.3.3 Chillers

Chillers are vapor compression refrigeration cycle equipment that produce chilled water. Pumps distribute the chilled water throughout the building through pipes to fan coil units or ducts. Chillers can be either water-cooled or air-cooled. Water-cooled chillers use water (condenser water) to transport the heat rejected from the compressor to a cooling tower which, in turn, rejects heat to the surrounding ambient air. Air-cooled chillers reject heat directly to the ambient air, using a condenser fan to circulate air over the condenser coil. Figure A-17 depicts a basic water-cooled chiller system.

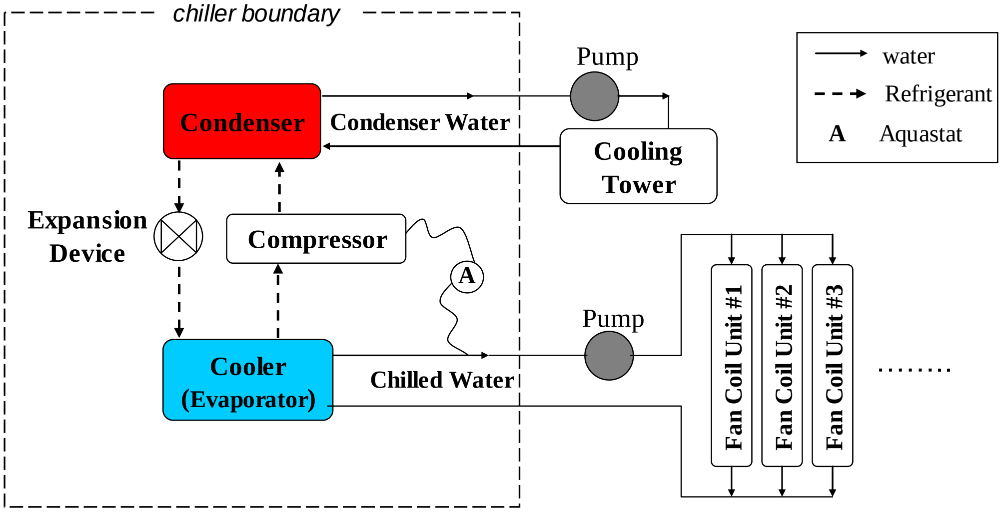

Figure A-17: Simplified Schematic of a Water-Cooled Chiller System

In the water-cooled chiller shown, water returning from the fan coil units (FCUs) exchanges heat with the cooler refrigerant in the evaporator through a heat exchanger. One or more pumps distribute the chilled water leaving the evaporator through pipes to multiple fan coil units in the conditioned spaces. In many systems, the chilled water flows to cooling coils

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[214] In many cases, constant blower operation throughout the heating season has been encouraged to improve air circulation, improve the uniformity of temperature distribution throughout the building, and to meet ventilation air requirements. However, constant blower operation increases electrical energy consumption and overall operating cost.

located in ductwork. In both cases, the FCUs or chilled water coils can be controlled individually or as a group to condition the air. A *chilled water temperature sensor* measures the chilled water temperature leaving the chiller and sends a signal to the compressor(s). If the chilled water temperature deviates from its set point, the chiller controls modulate the compressor(s) capacity to match the cooling load. The condenser water flows from the condenser to the cooling tower, which rejects heat to the ambient air. A temperature sensor detects the condenser water temperature leaving the cooling tower (returning to the condenser) and the cooling tower controls control fans, dampers or a water bypass valve to maintain the tower exit temperature near its set point. Condenser water flow is maintained to prevent fouling of the condenser coil from sediment, biological growth, and corrosive products. Chiller condensers typically allow for a certain degree of fouling, but excessive fouling impedes condenser heat exchange. Excessive fouling increases the temperature difference required to transfer a given amount of heat which, in turn, increases the required refrigerant temperature and increases chiller energy consumption.

It is important to note that Figure A-17 represents a simplified schematic of a chiller system. Actual chiller systems distribute water to multiple fan coil units or cooling coils, and may have multiple cooling towers or chillers. Section A.2.2 describes chilled water loops in somewhat more detail.

Many chillers use chilled water temperature reset to reduce chiller energy consumption. Temperature reset applies a relationship (e.g., linear) between the outdoor air temperature and the chilled water set point. As the outdoor air temperature rises or falls, the cooling load generally increases or decreases in a reasonably predictable fashion and the controller resets the chilled water set point according to this relationship. This enables the chilled water temperature to increase during periods of decreased cooling load, which decreases the temperature lift of the compressor and improves it operating efficiency.

In chilled water systems, a trade-off exists between the energy consumed by the compressor and that consumed by the cooling tower fans and chilled water pump[215]. By increasing the tower air flow, the condensing temperature can approach the outside wet bulb temperature, which decreases compressor energy consumption. On the other hand, this also increases the energy consumed by the condenser pump and cooling tower fans. Consequently, operators need to evaluate the energy consumed by the entire chiller system, i.e., including the water distribution and cooling tower, when applying chiller operation strategies, including water temperature reset strategies. It is possible to optimize chiller system efficiency; however, variations in system configurations complicate general optimization solutions.

Some chillers use an *antirecyle timer* to limit the starting frequency of the compressor. Repetitive rapid-starting cycles can damage both the compressor motor and compressor contactors. The chilled water piping can have a *water flow switch* to prevent cooler freeze-up under low- or no-flow conditions.

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[215] Typically, condenser water flows remain constant to prevent fouling of the condenser coil.

Chillers can also be characterized by the type of compressor used, i.e., reciprocating chillers use reciprocating compressors, centrifugal liquid chillers have centrifugal compressors, screw liquid chillers employ screw compressors[216], and scroll chillers use multiple scroll compressors. The mechanisms for modulating compressor capacity vary with compressor type. Reciprocating compressors have pistons driven directly through a pin and connecting rod from the crankshaft to increase the pressure and temperature of the refrigerant. A reciprocating compressor maintains a fairly constant volume flow rate over a wide range of pressure ratios. All reciprocating liquid chillers modify capacity primarily by combining cylinder unloading (i.e., not compressing refrigerant in a given cylinder) with on-off cycling of the compressor. Cylinders are loaded and unloaded by de-energizing and energizing the unloader solenoids that control refrigerant flow to the cylinders. If the cooling load decreases such that the return water temperature drops below a predetermined setting, the controls shuts down one or more cylinders until the demand for cooling increases. Unlike centrifugal and screw compressor chillers, reciprocating chillers use incremental capacity reduction (due to a finite number of cylinders) rather than continuous modulation. As a consequence, they require special arrangements to establish precise chilled refrigerant temperature control while maintaining stable operation free from excessive on-off cycling of compressors or loading-unloading of cylinders. Reciprocating chillers are available with multiple increments of unloading down to 12.5% in the largest multiple compressor units (i.e., for an eight-cylinder compressor). Most intermediate sizes provide unloading to 50%, 33%, or 25% capacity. Hot-gas bypass, i.e., allowing refrigerant vapor leaving the compressor to return to the compressor inlet through a valve, can reduce capacity to nearly 0% although it tends to increase energy consumption (ASHRAE 2000). For this reason, some building codes have banned hot-gas bypass.

Centrifugal compressors, sometimes called turbocompressors, use an impeller to increase the refrigerant's pressure and temperature. Most centrifugal chillers can modulate from 100% to approximately 10% load[217]. For capacity modification at constant motor speed, centrifugal liquid chillers commonly use prerotation vane modulation. Movable diffuser walls, gas bypass, and variable-speed drives are other ways to vary capacity at partial loads. Their ability to vary capacity continuously to match a wide range of load conditions with nearly linear changes in power consumption makes them desirable in situations demanding close temperature control. In addition, their low-capacity operation reduces compressor cycling. Centrifugal – as well as screw –chillers may include a *current limiter*, or *demand limiter* to cap compressor power draw and prevent current draw from exceeding the design value.

Screw compressors are rotary compressors that use a helically grooved main rotor and a gate rotor to compress the refrigerant as it moves through the casing. Screw compressor liquid chillers vary their capacity continuously with a slide valve that adjusts the length of

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[216] The text does not discuss absorption chillers because they account for less than 2% of commercial building cooling energy consumption (ADL 2001).

[217] Screw chillers also can use hot-gas bypass to reduce capacity to almost 0% with the unit operating (see the prior paragraph).

the compression path of the refrigerant within the main rotor. In some cases, screw chillers also use compressors with variable-speed drives to control capacity. Typically, however, part-load efficiencies degrade below about 40% of full load (ASHRAE 2000). Screw compressor liquid chillers exhibit stable operation over their working range, typically from 100% to approximately 10% load. As with reciprocating and centrifugal chillers, screw chillers can employ hot-gas bypass to reduce the capacity of screw chillers to nearly 0% with the unit operating.

Scroll chillers (typically air-cooled) have a small market share. In most cases, they have multiple compressors, in which case compressors are staged to vary chiller capacity.

A.3.4 Packaged Rooftop Units

Packaged rooftop units (RTU) are factory-assembled self-contained units that integrate various combinations of ventilation, heating and/or cooling. As their name implies, they are usually installed on the roofs of building. Most RTUs, including the one depicted in Figure A-18, use air to distribute heating and cooling to the conditioned spaces. A limited number of RTUs use chilled water as an intermediate cooling medium. Many packaged units provide heat either from a gas furnace, an electric resistive heating coil, or a heat pump.

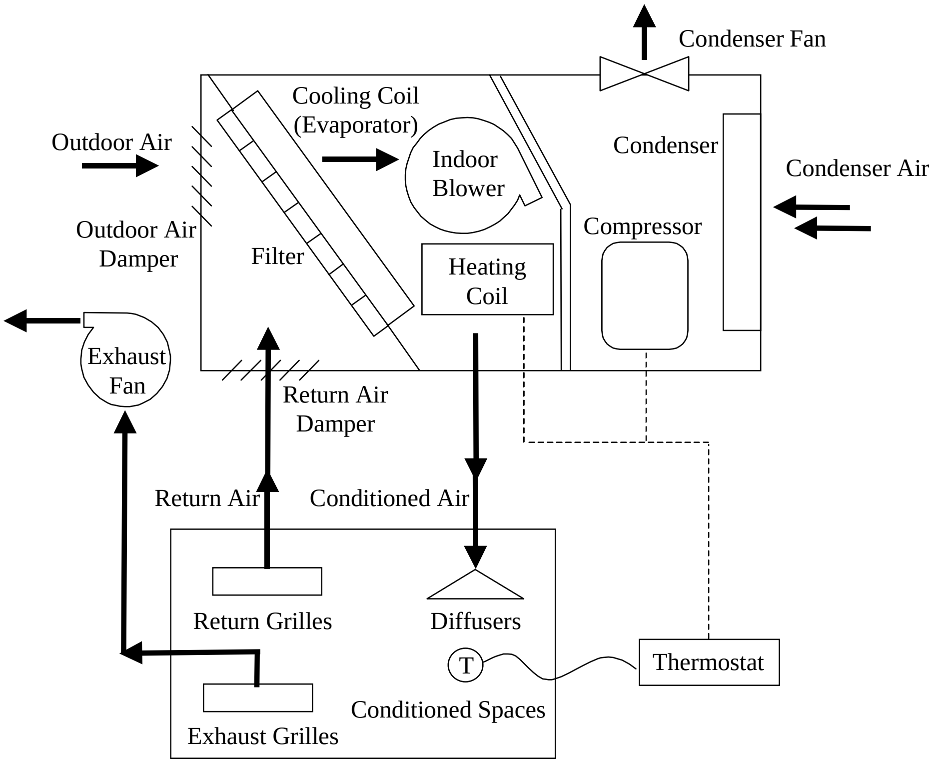

Figure A-18: Schematic of a Typical Packaged Rooftop Unit System

In this system, the blower induces air from both the outside and the conditioned spaces through the unit and pushes air into the building ducts. ASHRAE Standard 62 prescribes the volume of outdoor air (OA) for a given space and the RTU alters the amount of OA by controlling the position of the outdoor and return air dampers to obtain the desired OA volume (generally, the minimum OA volume is set at installation). After passing through at least one filter, the mixed air then flows through the cooling coil (evaporator), the indoor blower, then the heating coil. The conditioned air exits the unit into the conditioned spaces via ductwork and supply diffusers.

A vapor compression cooling circuit supplies cooling directly to the supply air through the cooling coil. The circuit then rejects heat to the outdoor air through the condenser coil using the condenser fan. Split systems have a somewhat different configuration from the unit shown in Figure A-18. Specifically, the condenser side (including the compressor condenser, condenser, and condenser fans) is usually located outside of the building while the evaporating side is located near or within the conditioned space.

A RTU that has both heating and cooling capabilities can operate in either cooling or heating mode. In the cooling mode, if the space thermostat senses that the temperature lies above its set point, the thermostat sends a signal to activate the compressor, the indoor fan, and the condenser fan. If the outdoor temperature (or, in some cases, enthalpy) lies below a second set point, which is typically at least several degrees below the space temperature setpoint, the RTU can employ an economizing strategy. In economizing mode, the RTU brings in OA with a lower temperature (and moisture content) than the return air to meet a portion of the cooling load, thereby reducing the load on the compressor. The RTU controls adjust both the OA and return air dampers to increase the quantity of OA entering the building. In the heating mode, the space thermostat senses the temperature and, when the temperature falls below the set point, sends a signal to activate the heating coil (either a resistive element or a furnace) that heats the conditioned space.

If the RTU supplies conditioned air to multiple zones, zone thermostats maintain the desired temperatures in each zone by either controlling the temperature (CAV) or the volume (VAV) of the air supplied to that zone. The "Central Air Handling Systems/Air Distribution Systems" section (Section A.2.1) discusses CAV and VAV systems in more detail.

A.3.5 Unit Heaters

Unit heaters are compact, relatively simple and inexpensive heating systems used for spaces with heating capacity requirements and/or large volumes that cannot be handled adequately or economically by other means. They often provide heat to spaces with higher ceilings, such as warehouses or industrial buildings. They have the ability to project heated air in a controlled manner over a considerable distance without ducting, which reduces system cost and frees up space for other uses. Figure A-19 shows the basic elements of a forced-air unit heater. In contrast, infrared or radiant space heaters have elements that radiate heat and usually do not have fans to drive convection heat transfer.

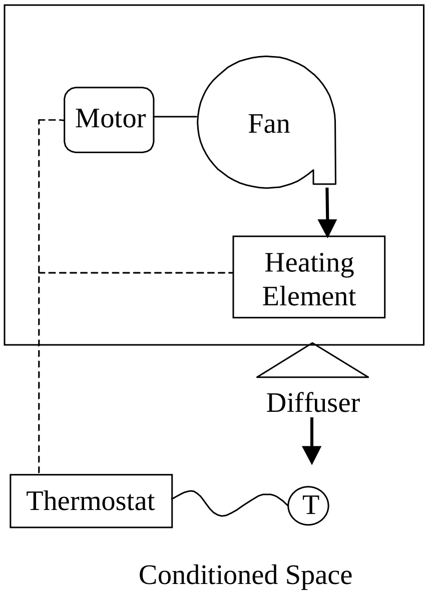

Figure A-19: Basic Unit Heater

Unit heaters can use steam, hot water, gas indirect-fired, oil indirect-fired, or electric heat. Most unit heaters in use today are either gas or electric, with gas being the most common. Electric and gas unit heaters account for similar percentages of unit heater *primary* energy consumption[218] in commercial buildings (ADL 2001a). Unit heaters also likely account for a significant portion of heating energy consumed in industrial settings.

Due to the large size of the conditioned spaces, thermostat placement is very important. Improper placement can often result in spots that are over- or under-heated by the unit heater. However, unit heaters are loud and can only be used where their noise is not prohibitive to the people or work conducted in the space

Similar to furnaces, gas unit heaters operate in response to primary and secondary controls. The primary control sensor is usually a thermostat that monitors the space temperature. When the temperature falls below the set point, the thermostat activates the burner. A fuel valve controls flow of the gas to the burner and the gas controls employed in a unit heater mimic those employed in a boiler or furnace, i.e. *on-off* control, *high-low-off* control, and *modulating* control. Similarly, a temperature-sensitive limit switch in the heated air stream shuts off the gas valve if the exit air temperature exceeds a predetermined threshold to prevent overheating if there is a severe reduction of circulating airflow.

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[218] This reflects the fact that an electric unit heater that delivers 100% of its heat to the space consumes about 2.5 times more primary energy than an 80% efficient gas-fired unit heater.

The secondary control switch activates the fan; it may be a temperature-sensitive switch exposed to the circulating air stream within the unit heater cabinet, or it may be an electronically operated relay. In both cases, the secondary controls typically start-up the circulating fan about one minute after burner activation. This delay allows the heat exchangers to warm up and avoids the circulation of cold air in the conditioned space. Similarly, the controls delay fan shutdown for several minutes after the burner shuts down to transfer residual heat from the heat exchangers to the conditioned space. One type of control used with downblow unit heaters automatically returns the warm air, which would normally accumulate at the ceiling, down to the occupied zone; this approach requires two thermostats and an auxiliary switch. Constant fan operation throughout the heating season has been encouraged to improve temperature distribution uniformity throughout the conditioned space. However, constant fan operation increases electrical energy consumption and overall operating cost.

Appendix B: Initial Fault List

Table B-1 is the initial fault list derived from an exhaustive literature search. A “fault” denotes a condition that causes improper systems or equipment operation and causes them to consume more energy than expected or intended. Inefficient equipment and systems are *not* faults, even though the do represent energy-saving opportunities.

The first column of Table B-1 categorizes each fault by equipment or system type in which the fault occurs and the second column briefly describes each fault. The third column of Table B-1 identifies energy end-uses that each fault could affect. It uses the following notation:

- L = Lighting;
- WH = Water heating;
- R = Refrigeration;
- V = Ventilation and pumping;
- H = Heating; and
- C = Cooling.

The fourth column, “Affected Energy,” provides an estimate of the total primary energy that the fault *could* affect. It reflects both the magnitude of energy of all the relevant end-uses and the market share of the system or equipment affected by each fault (see Table 8-2 for detailed breakdowns of energy consumption by end-use and equipment type). For example, economizers primarily affect the heating and cooling energy consumed by packaged systems (0.5 quads heating + 0.8 quads cooling = 1.3 quads total energy). If only 10%[219] of all packaged heating and cooling equipment have economizers, however, the affected energy for economizers equals approximately 0.13 quads (=1.3 quads * 10%).

Table B-1: List of Commercial Building System/Equipment Faults and Relative Rankings

Category	Fault Description	End-Uses Affected	Affected Energy [quads]
Chiller Systems (including cooling towers)	TXV failure/malfunction	C	0.4
	Refrigerant leakage/improper charge	C	0.4
	Excessive tube fouling/scaling	C	0.4
	Sensor errors (scale build-up, out of calibration, damaged)	C	0.4
	Refrigerant line clogging	C	0.4
	Improper setpoints (including lock-out setpoint)	C	0.4
	Improper chiller staging strategy (running largest chiller first, then using smaller chiller to meet additional load)	C	~0.1 (multi-chiller only)
	Manual control overrides (possibly accidentally left in effect after system maintenance)	C	0.4

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[219] This is an illustrative – not actual – value.

Category	Fault Description	End-Uses Affected	Affected Energy [quads]
	Non-optimized TXV setting	C	0.4
	Oversized chillers	C	0.4
	Compressor malfunction (esp. motor efficiency degradation)	C	0.4
	Dirty/damaged cooling tower coils	C	~0.3 (water-cooled only)
	Cooling tower fan motor malfunction/failure	C	~0.3
	Clogged cooling tower spray nozzles	C	~0.3
	Excessive bearing wear (indicated by vibrations)	C	0.4
	Compressor blade wear	C	0.4
	Low oil level	C	0.4
	Motor winding insulation degradation	C	0.4
	Clogged water-side strainers	C	0.4
Central Boilers	Excessive tube fouling/scaling	H	0.3
	Oversized boiler	H	0.3
	Damaged/dirty burner	H	0.3
	Clogged/damaged vent	H	0.3
	Leaky relief valve (seal degradation, operating too close to relief pressure)	H	0.3
	Clogged fuel strainers	H	0.3
	Fuel valves leak-by	H	0.3
	Air/fuel ratio drifts out of adjustment	H	0.3
	Baffle burn-through allowing hot gas to bypass HTX and go directly up the stack	H	0.3
	Ignition transformers get coated	H	0.3
Furnaces (incl. packaged heaters)	Worn/loose fan belts	H	0.8
	Blower motor malfunction/failure	H	0.8
	Damaged/dirty burner	H	0.8
	Clogged/damaged vent	H	0.8
	Oversized furnace	H	0.8
	Burn-through causing hot gas to bypass HTX and go up vent	H	0.8
Hydronic/ Steam Distribution Systems	Missing or damaged pipe insulation	C, H, WH, V	2.0
	Pump motor failure/malfunction	C, WH, V	1.7
	Valve actuator failure/malfunction	C, H, WH, V	2.0
	Valve leak-by / seal failure (i.e. flow occurs even when valve is in fully closed position)	C, H, WH, V	2.0
	Valve/joint leakage	C, H, WH, V	2.0
	Clogged filters/strainers/pipe	V	0.1
	Flowrate set too high/low	C, V	0.5
	Leaking steam trap	H	0.3
	Unbalanced flow	V	0.1
Air Distribution Systems (central AHU, ducts, dampers, etc.)	Missing or damaged duct insulation	C, H, V	3.1
	Damper actuator failure/malfunction	C, H, V	3.1
	Damper leak-by / seal failure (i.e. flow occurs even when damper is in fully closed position)	C, H, V	3.1
	Duct leakage (including at body of AHU)	C, H, V	3.1
	Dirt buildup on duct walls	V	0.8
	Airflow not balanced (can cause negative pressurization and lead to infiltration)	C, H, V	3.1
	Dirty/clogged filters	V	0.8
	Damaged/dirty AHU coils	C, H, V	0.8
	Blower motor failure/malfunction	C, H, V	0.8
	Worn/loose fan belts	C, H, V	0.8

Category	Fault Description	End-Uses Affected	Affected Energy [quads]
	High-efficiency pleated filters replaced with low-efficiency filters	V	0.8
	Undersized cooling coil	C	0.4
	Broken/disconnected damper linkages	C, H, V	3.1
Rooftop Unitary Equipment	Damaged/dirty coils	C, H, V	1.7
	Controller failure/malfunction	C, H, V	1.7
	Economizer failure/malfunction (disconnected linkages, broken actuator, etc.)	C, H, V	0.2
	Fan motor failure/malfunction	C, H, V	1.7
	Sensor failure/malfunction	C, H, V	1.7
	TXV failure/malfunction	C, H	0.2
	Refrigerant leakage/improper charge	C, H	0.9
	Air leakage at joints/seams of box	C, H, V	1.7
	Sensors out of calibration	C, H, V	1.7
	Worn/loose fan belts	C, H, V	1.7
	Refrigerant line clogging	C, H	0.9
	Excessive fresh air supply rate	C, H, V	1.7
	Mixed air damper failure/leak-by	C, H, V	1.7
	Improper OA sensor placement (in the sun or in an exhaust air path)	C, H, V	1.7
	Improper economizer setpoints (including lock-out setpoint)	C, H, V	0.2
	Improperly tuned controls (e.g. PI gains too large = “hunting”)	C, H, V	1.7
	Simultaneous heating/cooling (controller logic error)	C, H, V	1.7
	Non-optimized TXV setting (improperly tuned)	C, H	0.4
	Improper jumper wiring in controller	C, H, V	1.7
	Motor windings malfunction (loss of insulation, corroded contacts, etc)	C, H	0.9
	Loss of compressor lubrication	C, H	0.9
	Compressor leak-by (hot gas bypass)	C, H	0.9
Zone Equipment (fan-coil units, unit heaters, RACs, terminal units)	Damaged/dirty coils	C, H, V	2.2
	Fan motor failure/malfunction	C, H, V	1.0
	Reheat valve stuck open	C, H	~0.4
	24hr fan operation	V	~0.1
Water Heaters	Excessive tube fouling/scaling	WH	1.2
	Setpoint temperature too high	WH	1.2
	Missing/damaged tank/pipe insulation	WH	1.2
Refrigeration Equipment	Damaged/dirty coils	R	0.6
	Sensor failure/malfunction	R	0.6
	TXV failure/malfunction	R	0.3
	Improper refrigerant charge/leakage	R	0.6
	Sensors out of calibration	R	0.6
	Refrigerant line clogging	R	0.6
	Condenser fan motor malfunction/failure	R	0.6
	Compressor malfunction (loss of efficiency)	R	0.6
	Non-optimized TXV setting	R	0.3
Lighting	Occupancy/photo sensor failure/malfunction	L	0.5
	Sensors out of calibration	L	0.5
	Lights left on when not occupied (either no BAS/schedule or schedule not enabled/overriden)	L	3.4
	Improper occupancy sensor placement	L	0.4
	Improper photo sensor placement	L	0.1

Category	Fault Description	End-Uses Affected	Affected Energy [quads]
	Improper timeout setting on occupancy sensors	L	0.4
	Manual control overrides (e.g. occupants turn off occupancy sensor)	L	0.5
	Illumination of areas that do not need to be lighted (light escaping from the fixture, improper design of lighting layout)	L	3.4
	Dirt accumulates on bulb, lens, and reflectors (light output degradation)	L	3.4
Central Control Systems (EMCS, BAS, etc. – excluding refrigeration, WH, and lighting controls - ~40% of floor area has BAS)	Clocks drift out of sync (causing back and forth overrides when unoccupied)	C, H, V	1.8
	Reset temperatures not enabled	C, H	1.2
	Sensors missing, not connected, or not connected properly (zone damper hooked up to wrong thermostat, return air temp sensor plugged into supply air node of EMCS, etc.)	C, H, V	1.8
	Improper thermostat placement	C, H, V	1.8
	Controller failure/malfunction	C, H, V	1.8
	Sensor failure/malfunction	C, H, V	1.8
	Wiring/communications failure	C, H, V	1.8
	Sensors out of calibration	C, H, V	1.8
	Data loss from inadequate communications bandwidth or bad connections	All	1.8
	Improper scheduling/schedules not enabled	All	1.8
	Improper temperature/pressure sensor placement in ducts/pipes	All	1.8
	Improperly tuned controls (e.g. PI gains too large = “hunting”)	All	1.8
	Non-optimized start/stop sequencing	All	1.8
	Software programming errors/breakdowns in control logic (“and” instead of “or” can cause simultaneous heat/cool or operation of reheat coils year-round for example)	All	1.8
	Missing sensors	All	1.8
	Improper jumper wiring in controller	All	1.8

Appendix C: List of Publications Consulted

The detailed literature review consulted the publications listed in Table C-1, as well as several other books and university report/theses.

Table C-1: List of Publications Consulted During the Detailed Literature Review

Conference Proceedings	*ACEEE Summer Study on Energy Efficiency in Buildings*
	ASHRAE Annual Meeting
	International Conference on Improving Electricity Efficiency in Commercial Buildings (IEECB)
	LBNL Diagnostics Workshop (1999)
	National Conference on Building Commissioning
	Right Light
Journals	*ACHR News*
	ASHRAE Journal,
	ASHRAE Transactions
	ASME Journal of Solar Energy Engineering
	AutomatedBuildings.com
	Buildings
	Building Operating Management
	Building Serv. Eng. Res. Technology
	Energy and Buildings
	Energy Conversion & Management
	Engineered Systems
	Hotel and Motel Management
	HPAC Engineering / Networked Controls
	J. of the Illuminating Engineering Society of North America
	LD+A
Reports	American Council for an Energy Efficient Economy (ACEEE)
	Arthur D. Little Reports
	ASHRAE
	Building Owners and Managers Association (BOMA)
	California Energy Commission
	Continental Automated Buildings Association (CABA)
	Energy Design Resources (Design Briefs)
	International Energy Agency (IEA)
	Iowa Energy Center
	Lawrence Berkeley National Laboratory (LBNL)
	Lighting Research Center (LRC)
	National Institute of Standards and Technology
	Northwest Energy Efficiency Alliance
	Pacific Northwest National Laboratory (PNNL)
	Portland Energy Conservation, Inc. (PECI)
	Texas A&M University, Energy Systems Laboratory
	U.S. Department of Energy, Office of Building Technology

Appendix D: Energy Prices and Demand Charge Impact

Energy prices have a major affect on simple payback period (SPP) calculations, as they translate energy savings into annual energy cost savings. Historically, energy prices have fluctuated over time, which complicates SPP calculations (see Figure D-1; note, these are *nominal* prices, i.e., not adjusted for inflation). They also exhibit substantial geographical and seasonal variations. Nominal gas and electric prices in the U.S. have stabilized somewhat since the 1980s and the current average electric price in the commercial buildings sector lies somewhere between seven and eight cents per kilowatt-hour (kWh). The average natural gas rate has fluctuated between five and six dollars per million-BTUs. The recent data from the Energy Information Administration (EIA; November 2002) shows average **electric rates near $0.08/kWh** and natural gas prices close to **$6/MMBtu** and those values are used for the SPP calculations.

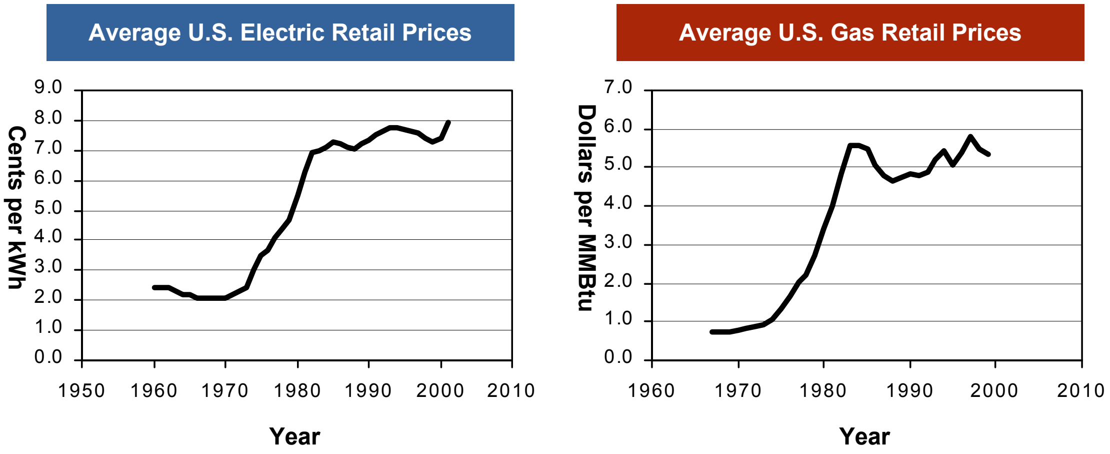

Figure D-1: Average Commercial Electric and Gas Prices in the U.S. (nominal; from EIA 2002)

For most commercial buildings, the electric price consists of a usage component ($/kWh) and a demand charges ($ per peak kW). Demand charges vary greatly from utility to utility, and so the impact of control approaches that reduces peak demand on cost savings varies as well. A review of electric rate structures in six major U.S. cities (Chicago, Los Angeles, Miami, New York, Phoenix, and San Francisco) for both small and large commercial customers found that demand charges are common, especially for larger customers. The magnitude of the demand charges varies by utility, typically in the range from $5 to $15/kW of peak demand during summer months, with smaller demand charges during the winter). Based on this, a typical demand charge in the U.S. equals approximately $10/kW during the summer and $5/kW during the winter.

A review of TIAX building load databases for offices, retail buildings, hospitals, schools, and hotels reveal load factors[220] typically lie between 0.35 and 0.45. Using 0.4 as a typical

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[220] Load factor equals the electric consumption (kWh) in any given time period divided by the product of the peak load (kW) and the number of hours in the time period.

load factor combined with a \$10/kW demand charge and a \$0.08/kWh total charge yields the following per-kWh monthly bill:

Monthly electricity cost (per kWh) = \$0.08 = \$10/kW x 0.00336[221]kW/kWh + \$0.0464/kWh.

In this case, the ratio of the demand charge (\$0.0336) to the total charge (\$0.08) equals about 0.4[222], i.e., peak demand charges account for roughly 40% of total electricity expenditures on average. Consequently, a 1% reduction in peak demand reduces annual electricity expenditures by 0.4%.

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[221] 0.00336 equals 1/(load factor[0.4] x hours per month [~744]) and \$0.0464 is the difference between \$0.08 and the product of \$10 x 0.00336.

[222] %. This relationship does not hold for extreme peak reductions that will notably impact the load factor, but represents a reasonable approximation for peak reductions of up to ~10%.

Appendix E – Fault Energy Impact Data and References

This Appendix contains the data found from all of the sources consulted for each fault, as well as the complete reference for each fault. Table E-1 indicates the pages for information relation to each specific fault.

Table E-1: Pages for Specific Faults

Fault	Page
Lights or HVAC Left on When Space Unoccupied	E-1
Duct Leakage	E-7
Dampers not Working Properly (Actuator failure, blades stuck, etc.)	E-12
Airflow Not Balanced	E-16
Insufficient Evaporator Airflow	E-17
Software Programming Errors	E-19
Improper Controls Hardware Installation	E-21
Improper Controls Setup / Commissioning	E-25
Control Component Failure or Degradation	E-32
Valve Leakage	E-36
Air-Cooled Condenser Fouling	E-38
Improper Refrigerant Charge	E-39

E.1 Lights or HVAC Left on When Space Unoccupied

Fault Energy Impact Data

Table E-2: Energy Impact Data for HVAC and Lighting Operation During Unoccupied Hours

Source	Key Information	Application Context
Architectural Energy (2003)	30% of supply fans ran during unoccupied periods	Comparison of fan and building occupancy schedules for 215 small RTUs in California
Arney and Frey (1997)	RTUs turned on too early and shut off too late; ran all day on Christmas and New Year's Days	125kft^2 building with 8 RTUs, 4 studied for two weeks (only RTUs studied)
Arney et al. (1999)	RTUs running well beyond expected schedules (e.g., late evening, Sunday); total energy savings for fixing all faults (including economizer operation issues, lockout on DX compressors below 50^{o}F, and lockout on baseboards above 60-65^{o}F) ~17% of building lighting and HVAC system energy.	60 kft^2 4-story office building near Baltimore, built in 1987, identified as having higher energy bills than other buildings in office park
Arney et al. (1999)	50% of lights left on all night	60 kft^2 4-story office building near Baltimore, built in 1987; identified as having higher energy bills than other buildings in office park
Butler (1997)	Space temperature did not set back at night during winter –programming schedule saved $13.2k/year; some fans running unnecessarily – reduction saved ~$500/year	958 kft^2 Honeywell corporate campus, 8 multi-story buildings, ~600 control points, Minneapolis

Source	Key Information	Application Context
EIA (1999)	Approximately 12% of time-weighted (for occupied hours) floorspace lit when unoccupied	Building surveys for >5,000+ buildings; assumes same kWh/ft^2 for all floorspace
Churchill (2000)	Systems operating at night, 24% total energy bill savings when fixed. Another school reduced total bill by ~13%; estimates that ~1/6th of schools have "dysfunctional" DDC systems	Schools in Oregon
Claridge et al. (1994)	Scheduling issues for AHU, Exhaust, Lighting, Office Equipment, 11.5% savings estimate	8 Austin Texas State Buildings
Claridge et al. (1996)	EMCS disabled, preventing night shut-down of lighting and HVAC	A "large majority" of 45 schools in North Texas
Claridge et al. (1996)	Light shutdown annual savings of ~$55k/year for all buildings	Eight government office buildings in Austin, TX, ranging from 80k to 491kft2, totaling ~2,000kft2;
Claridge et al. (1996)	Night shutdown saved $328k per year in AHU energy consumption	Four of Eight government office buildings in Austin, TX, ranging from 80k to 491kft2, totaling ~2,000kft2;
Claridge et al. (1996)	Night shutdown of HVAC and lights could save $43k and ~$8.5k per year in two schools (combined)	The two monitored (of 45 total) school buildings in North Texas that had had lighting retrofit; identified by lower-than-expected energy savings
Claridge et al. (1999)	10% to 20% of buildings have equipment shutoff opportunities	Personal judgment based on many whole building energy consumption and diagnostics studies (primarily larger buildings)
Eley Associates (2002)	24-hour operation increased total HVAC electricity consumption by ~100% and space heating by ~300% as compared to a “normal” 5-day schedule[223]	DOE 2.2 S simulations of a 105kft^2 office building in California with a VAV system
Energy Design Resources (2000)	Burn hours 50-72% greater than scheduled utilization for Halls and Lobbies; 29-46% less than schedule utilization for Private areas and Conference Rooms.	Based on Owashi et al. (1994), "Lighting Hours of Operation . . ."
Energy Design Resources (2000)	Occupancy sensor savings: Private Office 13-50%; Open-Plan Office 20-28%; Classroom 40-46%; Conference Room 22-65%; Rest Room 30-90%; Corridors 30-80%; Storage/Closet 45-80%	Based on U.S.EPA, "Advanced Lighting Guidelines"
Friedman et al. (2002)	6 had scheduling problems	10 buildings commissioned (5 in CA, 5 in Pacific NW) between 1996-2000; other problems also noted
Haasl and Edmunds (1997)	Adding HVAC and AHU scheduling to new EMCS saved ~$52k/year	175 kft^2 state office building, 7 stories, Tennessee, built in 1950 and 1970; built-up system, 19 AHUs, EMCS, 2-300 ton chillers, 418 under-window ventilators
Haasl et al. (1996)	Poor RTU schedule, waste ~$2,500/year	107 kft^2 Massachusetts retail, 4 years old; propane furnace, DX RTUs, non-ducted CV air system, EMCS; ~$255k/year energy expenditures
Haasl et al. (1996)	Poor scheduling wastes ~$6,200/year	250 kft^2 Tennessee office buildings, 11 years old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures

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[223] Hours unspecified; results for “No [Supply Air] Reset” strategy. Adopting “Reset by Warmest Zone” and “Reset by OAT” strategies decreases differences significantly. Percentages are rough estimates from plot (data available only 24-hour schedule).

Source	Key Information	Application Context
Haasl et al. (1996)	Unneeded lighting at night, wastes ~$3,100/year	250 kft^2 Tennessee office buildings, 11 years old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures
Haasl et al. (1996)	Poor stairwell exhaust fan schedule, wastes ~$2,400/year	250 kft^2 Tennessee office buildings, 11 years old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures
Haasl et al. (1996)	Poor lighting control schedule, wastes $1,725/year; poor parking garage exhaust fan schedule wastes ~$660/year	80 kft^2 Arizona office building, 9 years old; natural gas boiler, 2 cooling towers, hydronic heat pump, electronic control w/ time clock; ~$156k/year energy expenditures
Haasl et al. (2001)	(1) Scheduling for zones not serving computer labs, 6.2% energy savings; (2) Scheduling and by-pass timers 14% energy savings; (3) scheduling for equipment AND lights, 9.6% energy savings.	(1) Campus of a high tech company in Portland, Oregon; (2) Hospital in Northern California; (3) Three office buildings in Massachusetts.
Houcek et al. (1993)	Calculations show that shutting off lights in the evening will reduce total energy cost by 1% for all 8 buildings	Potential O&M savings for a complex of 8 state building in Texas
Khan et al. (2002)	Lights observed to remain on at night in 10 unoccupied spaces; 21,900kWh/year reduction estimate	45 kft^2 California Long-term Care Facility
Khan et al. (2002)	Several areas of facility had lights on during periods of extended vacancy; Energy savings estimated at 14,400kWh/year	California long-term care facility; 15 3-5 ton RTUs, 30 kft^2
Liu et al. (1993d)	Analysis shows that shutting off the lights in the evening and installing motion sensors will result in 7% savings from the total annual energy cost	a study of potential cost savings in two schools in Texas, 93kft^2 and 62 kft^2
Liu et al. (1993d)	An analysis shows that shutting off the HVAC in the evening will result in 33% savings from the total annual energy cost	Two schools in Texas, 93 kft^2 and 62kft^2
Liu et al. (2004b)	Found that 16 of 25 AHUs could be shut down for 6 hours at night	11-story government building in Austin, TX; 470kft^2
McGuire et al. (1995)	49% (79/162) of the deficiencies found were scheduling issues; fixing the problem resulted in total annual cost savings of $70,000	162 deficiencies in 33 buildings in NY
Parks and Kellow (2000)	Lighting schedule issues	Four SMUD-area buildings; not broken down by building or frequency/# of buildings. Buildings selected because: >100kft^2, energy-intensive, had EMCS, interested staff, owner willing to invest $10-20K in improvements
Parks et al. (2003)	24% of the electric energy was saved when scheduling and occupancy control was implemented and setpoints were raised	Retrocommissioning study of a crime laboratory in Sacramento, CA in 1999
Rojeski and Groover (1999)	Both EMCS were not operating -> AC systems operated around the clock	Two 20-year old 20kft^2 army administration buildings, in NC
Santos and Rutt (2001)	Two occupancy-based anomalies found [unclear if lighting or HVAC], both occurred during setup	AFDD applied during a 6-month period to 8 AHUS (230,000cfm total) at a pharma campus in the Midwest
Seattle City Light (1997)	Lighting sweep control in "chaos"; override zones "frequently improperly assigned if … assigned at all"	New 85 kft^2 new government office building, Portland, OR
Seattle City Light (1997)	EMCS control of refrigerated case lighting omitted; unclear if turned off manually or not	Refrigeration system of 60kft^2 grocery store in Utah
Warren (2003)	Occupancy average 10 percent in hallways and stairways of apartment buildings.	Stairways and Corridors of high rise apartment buildings
Zhu et al. (1997)	8 single-duct CV AHUs serve ~10% of conditioned area ran all the time; Changed static pressure and VFD speed setback to 50% during unoccupied periods	360kft^2 (conditioned space) office building in Austin, TX, built in 1992

Table E-3: SBW Consulting (2003) Data for HVAC and Lighting Operation During Unoccupied Hours

Source	Key Information	Application Context
SBW Consulting (2003)	AHUs on 24 hours/day when not needed [save ~18,550kWh/year]; Holiday schedule not programmed [save 37,700kWh/year, 3,250 therms/year]	ID-ACC: New 340kft^2 Idaho courthouse
SBW Consulting (2003)	"Some" non-emergency lights still on when entire building turned off via controls (~5 rooms mentioned);	ID-BSU: New 90kft^2 Idaho recreation center
SBW Consulting (2003)	EF-7 and EF-15: runs continuously (schedule has no effect)	ID-NAM: Retrocommissioning of a 23kft^2 office building in Idaho
SBW Consulting (2003)	MH lamp fixtures in solvent rooms have long strike time, fixtures "generally" on all the time [fixing saves ~7,100 kWh/year]; helicopter tarmac lights left on all time (for security originally, no longer needed) [save 28,645kWh/year]	MO-AAS: Retrocommissioning of 56kft^2 maintenance facility in Montana
SBW Consulting (2003)	2 of HV units operate at low speed 24 hours/day	MO-AAS: Retrocommissioning of 56kft^2 maintenance facility in Montana
SBW Consulting (2003)	Excessive HVAC use during unoccupied hours	MT-UMG: Retrocommissioning of U of Montana academic building, 110kft^2
SBW Consulting (2003)	Two instances of excessive HVAC use during unoccupied hours due to poor control settings and auto-control override.	MT-UMG: Retrocommissioning of U of Montana academic building, 110kft^2
SBW Consulting (2003)	Excessive HVAC use during unoccupied hours, 21 AHUs (out of 30) were all found overridden to the Occupied mode, implementing scheduling will save 190,000 kWh/yr and 10,000 therm/yr	MT-UMG: Retrocommissioning of U of Montana academic building, 110kft^2
SBW Consulting (2003)	Two Stairwell cabinet heaters (unclear total) overridden to the Occupied mode	MT-UMG: Retrocommissioning of U of Montana academic building, 110kft^2
SBW Consulting (2003)	Five fan coil units (unclear total) overridden to the occupied mode.	MT-UMG: Retrocommissioning of U of Montana academic building, 110kft^2
SBW Consulting (2003)	One FTU unoccupied heating setpoint equals 70°F.	MT-UMG: Retrocommissioning of U of Montana academic building, 110kft^2
SBW Consulting (2003)	1 of 4 AC RTUs ran all night for no apparent reason from 11/9/00 to 11/10/00 without morning warm-up	OR-CHS: New office building in Oregon, 160kft^2
SBW Consulting (2003)	Another 1 of 4 RTUs runs all night for no apparent reason, energy waste of 112,000 kWh/yr and 4,200 therm/yr	OR-CHS: New office building in Oregon, 160kft^2
SBW Consulting (2003)	One fan-powered terminal box (unknown total) has a thumb-wheel setpoint failed diagnostic alarm since 12/16/00. Electric box heat cycles on when box status is unoccupied, even when AC-3 is off and flow sensor indicates 0cfm. Discharge air temperatures indicate that box heat operates outside of time of day scheduling. Box status changes between occupied, unoccupied, and optimal start, regardless of time of day scheduling.	OR-CHS: New office building in Oregon, 160kft^2
SBW Consulting (2003)	Another fan-powered terminal box (unknown total) has a thumb wheel set point failed diagnostic alarm since 12/16/00. Electric box heat runs overnight when box is scheduled unoccupied and airflow is 0cfm.	OR-CHS: New office building in Oregon, 160kft^2

SBW Consulting (2003)	AC-1 fan comes on for no apparent reason when the unit is scheduled in unoccupied mode in the evenings; does not occur every evening, may occur several times on the same evening. Fan cycles on/off in 5-10 minutes.	OR-SKS: New elementary school in Oregon, 49kft^2
SBW Consulting (2003)	TU boxes occasionally call for heating or cooling when scheduled to be unoccupied, either before morning warm-up or after AC units are scheduled off.	OR-SKS: New elementary school in Oregon, 49kft^2
SBW Consulting (2003)	One motion sensor had the lights on and the HVAC unoccupied.	WA-BIH: New high school in Washington, 144kft^2
SBW Consulting (2003)	3-way pneumatic control valve lacks time clock control; piped to drain compressor when in night mode which causes compressor to run continuously.	WA-BIH: New high school in Washington, 144kft^2

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E.2 Duct Leakage

Energy Impact Data

Table E-4: Energy Impact Data for Duct Leakage

Source	Key Information	Notes
Carl and Smilie (1992)	4 of 8 restaurants; 4 of 8 grocery stores; 0 of 7 motels[225] had significant duct leakage	• Mixture of split AC and RTUs • In Louisiana
Hewett et al. (1992)	Duct leakage "appreciably degrading" performance in 7 systems; 6 systems "generally tight"	• 18 light commercial AC units with 25 compressor circuits in New England; all at least 4 years old • Duct for 5 units located entirely in conditioned space
Caner (1996)	38% (6/16) of AHUs had air leaks at duct penetrations; annual energy impact of 1,000 kWh and 600 therms	One academic building in WA; no information on total building annual energy consumption
Cummings et al. (1996)	• ~19% duct leakage (~70 times greater than SMACNA[226] standard) • T-bar ceiling support systems (in ceiling plenums) particularly leaky	• Field measurements of 46 small commercial Florida buildings • Duct location breakdown (of 70): 17 within the thermal and air barriers, 48 in unconditioned portions, 2 outdoors • 34 of 70 buildings use building cavities for some portion of air flowpath • Air handler locations (for 70 buildings): 20 on roof; 29 in mechanical closet or room[227].
Carcaterra et al. (1997)	• Rooftop plenum enclosures leaked, including lab hoods and energy recovery unit; "numerous" leaks of AHUs on roof	• New 179kft2 [78kft2 office, ~99kft2 research] building in College Park, MD
Delp et al. (1997)	• All systems had ducts located in cavity between drop ceiling and roof deck; 50% of ducts effectively outside building’s air and thermal barriers • ALR averaged 26%; ALR uncertainty ~+/-5%	• Field measurements of 15 light commercial systems in 8 Northern California buildings • Average unit size of 3.9 tons

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[224] An energy management analyst for the City of Seattle notes that the studies were all completed in or before1997.

[225] Hotels often use PTACs, which do not have ducting.

[226] SMACNA is short for the Sheet Metal and Air Conditioning Contractors' National Association.

[227] The remaining units: 5 outdoors; 6 in occupied space, 4 in attic, 2 in ceiling space, 3 in unconditioned warehouses.

Source	Key Information	Notes
Delp et al. (1998b)	Visual inspection-based ratings of the duct condition did not correlate well with actual leakage levels	• 25 RTUs in 16 small commercial buildings, in Northern California, all CAV • 56% of buildings, duct outside conditioned area; 25%, thermal barrier and ducts both in between roof and ceiling.
Delp et al. (1998a)	No detectable leakage, with no detectable energy impact	• Field measurement of a single AHU with 8 tons cooling capacity serving a single-story college building (1,580ft^2) • 75% of duct on roof
Fisk et al. (1998)	• ALR ranged from 0 to 30%, with most systems between 10 and 20% • ALR maximum uncertainty ~+/-10%	• Field measurement of 8 large commercial systems in 6 buildings • Large variations of leakage with measurement technique
Modera et al. (1999)	• Leakage flow: Supply - ~8% and 26%; Return - ~25% and 51% • From 35 to 65% of duct run located outside conditioned space	• Field measurements of 3 packaged 5-ton rooftop systems in 2 Northern California strip mall stores
Xu et al. (1999)	ALR of 0% to 30% reported for the two duct systems (includes estimated uncertainty of ~+/-16%)	• Field measurement of two large CAV systems in Northern California • Large variations of leakage with measurement technique and very large measurement uncertainties
Rojeski and Groover (1999)	For one AHU, nearly 50% of supply air leaked into unconditioned areas	• Two 20-year old 20kft2 army administration buildings, in NC
Modera (2000)	Recommended assuming that large commercial building ducts lie within conditioned space	•
Xu et al. (2000)	Average ALR ~10%, standard deviation of ~6% (i.e., 10% +/- 6%); ALR uncertainty of +/-13-16%	• Field measurements of 5 light commercial systems in 4 Northern California buildings
Jacobs and Williams (2002)	85% of the systems had excessive duct leakage	• a study of 350 small commercial HVAC systems in southern California
Khan et al. (2002)	"several" RTUs showed "significant" leaks from supply duct	• 45kft2 California Long-term Care Facility
Luskay and Sellers (2002)	Poor plenum sealing led to insufficient plenum pressurization, causing AHU VSD to operate at 100%	• Renovated 11kft2 office space (one floor of bldg.) to include underfloor air distribution
Luskay and Sellers (2002)	16-18% leakage to unconditioned area	• New underfloor air distribution system with: 15kft2 office, 25kft2 training center, and 135kft2 distribution center
Modera and Proctor (2002)	• At least 82% of systems had duct leakage ratio of 24% or more, average leakage ratio of 36% (for 82% of systems); remaining systems tested (i.e., of the 18% with <24% duct leakage) had an average leakage ratio of 18% • Unclear but likely small uncertainty in ALR – based on calibrated blower testing	• 447 light commercial A/C duct systems in Southern California
Architectural Energy (2003b)	Less than 10% of new light commercial buildings (excepting warehouses) have ducts located outside the conditioned space	• *New* light commercial buildings in California
Diamond et al. (2003)	• Duct leakage totaled 5% of air handler flow at operating conditions • Installed ALR of 20% (from 5% baseline) increases total fan power consumption by 19% over entire day, by 26% during peak periods • Installed 11-16% ALR (5% baseline) increases total (daily) fan energy by 12-17% • Leakage downstream of VAV boxes increases total fan energy more than upstream leakage • Branch ducts much leakier than supply loop (roughly 20-fold higher leakage class)	• Measurements from two floors (25kft^2 each) of a 25-story office building in Northern California • Variable-speed supply AHU with VAV boxes • Powered flow hood measurements had a +/-2% uncertainty (absolute) in ALR

Source	Key Information	Notes
SBW Consulting (2003)	- Access door on supply duct in mechanical room leaking "a lot" of air; traverse holes in ducts (unclear prevalence) - Overall duct leakage estimated at ~10% based on supply vs. diffuser measurements [save ~62,700 kWh/year, 400 therms/year];	- New 90kft^2 Idaho recreation center
Wray and Matson (2003)	- See Appendix to this section for simulation results of how different levels of duct leakage impact ventilation, cooling, and heating energy consumption	- TRNSYS modeling of a VAV system with supply ducts located in a return air plenum - Office buildings located in three California climates
Wray (2004)	- 5% represents “good” duct sealing practice - LBNL has measured buildings with as low as 3% leakage (CAV systems) - Very roughly, 50% of all larger commercial building have well-sealed ducts	- Small sample of larger commercial buildings, primarily located in California

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E.3 Dampers Not Working

Energy Impact Data

Table E-5: Energy Impact Data for Dampers Not Working

Source	Key Information	Application Context
Ander and Bruder (1996)	Economizer dampers sticking (open or closed)	Commissioning of new 130kft2 WalMart in Southern California – focus on lighting controls, HVAC and EMCS
Arney et al. (1999)	Economizers not functioning in 3 of 4 RTUs	60kft2 4-story office building near Baltimore, built in 1987; identified as having higher energy bills than other buildings in office park
Barwig et al. (2002)	Estimates that failure rates of economizers 50% and higher with energy waste far exceeding energy savings when operating properly	Literature review: Lunneberg (1999)
Breuker and Braun (1998)	Approx. 7% of failures were air handling failures resulting in 5% of total service costs.	More than 6000 separate fault cases for rooftop units from 1989-95 for large commercial chain stores
Butler (1997)	Leaky AHU dampers - repair/adjustment saved ~$1k/year	958kft2 Honeywell corporate campus, 8 multi-story buildings, ~600 control points, Minneapolis
Caner (1997)	Over 200 damper actuators were replaced in one building and roughly 40% (120/300) actuators were replaced in another building	commissioning of 4 academic buildings in Washington
Casault (1997)	Welded steel linkage of fan volume control cone fails	New 75kft2 library
Consortium for Energy Efficiency (2001)	Approx. 75% of rooftop units suffer from economizer malfunction, which can result in energy use higher than without an economizer	Research conducted on commercial packaged 3-20 ton units over 100 sites in the Northeast
Davis et al. (2002a)	Economizer dampers did not function properly on 7 of 20[228] units evaluated for damper function (2 – dampers installed fixed fully open; 2 – dampers open fully when compressor runs; 3 – malfunctioning microswitches economizers inoperable). Estimated 26% of annual cooling energy savings by fixing damper problems and using 60°F changeover from outside air to compressor-only cooling, 14% for 55 °F changeover	23 packaged rooftop units, most CV, from 2.5-15 tons, several vintages, one split unit; Eugene, OR
Delp et al. (1998)	84% of units did not have OA provisions or had dampers shut permanently	25 RTUs in 16 small commercial buildings, in California, all CAV

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[228] 3 units had remotely-operated dampers that could not be evaluated.

Source	Key Information	Application Context
Financial Times Energy (2003)	Economizers save 2 to 9 percent as compared with constant outdoor ventilation for office space. Potential waste for economizers stuck in the open position can be on the order of 50% of cooling season energy, additional waste for heating season. Peak load increase for a Bakersfield CA office building for a stuck open economizer would be up to 84%. Citation of an HEC/NEES survey of Northeast buildings (22 sites and 52 units) in which only 44% of economizers were working "a year or two" [after installation].	
Fish (1999)	OA dampers blocked open	5kft2 animal research and services bldg., Northwestern US (it appears; not certain)
Goody et al. (2003)	37% of *all* economizers considered “failed” Breakdown of Economizer Problems includes [percentages of units *with* problems]: 50% - Improper changeover setting (usually low, i.e., no economizer function) 5% - Actuator / controller 10% - Outdoor air sensor failure 5% - Seized damper 10% - Improper setup or install 5% - No power 2% - Llinkage	54 rooftop units in the Northwest – 65% had had economizer problems
Houghton (1997)	A study of 13 rooftop units on small commercial buildings found 100% had improperly operating outside-air dampers	(no other info on location)
Jacobs et al. (2003)	43 units (34%) had poorly operating dampers	123 of the 215 rooftop units tested had economizers (in 75 newly constructed buildings in CA)
Jacobs (2002)	70% of units had broken economizers	140 rooftop units on 40 new commercial buildings in California
Kjellman et al. 1995)	Damper motor linkages in 70% (5/7) of the buildings were disconnected/broken	a study of 7 buildings in S. California
McGuire et al. (1995)	17% (27/162) of the deficiencies were faulty dampers, fixing the problem resulted in total annual cost savings of $11,000	162 deficiencies in 33 buildings in NY state
Piette et al. (2001)	Lack of supply air damper control led to cold deck backdraft	Continuous monitoring of EMCS data from two office towers in Oakland, 971k ft2 office space, 7.2k computer center; 5 chillers; won Energy Star Label without major retrofits
Piette et al. (2001)	Two Units: Economizing not working properly	Continuous monitoring of EMCS data from two office towers in Oakland, 971k ft2 office space, 7.2k computer center; 5 chillers; won Energy Star Label without major retrofits
Pratt et al. (2000)	1 AHU damper stuck fully open (leading to excessive OA); another stuck fully closed;	6 AHUs in a large SF hotel; selected because of economizer usage and spaces served, NOT prior evidence of faults
Rojeski and Groover (1999)	Damper linkages disconnected on 6 of 8 multizone AC units; Supply air temps fixed by manual position of mixing dampers; most dampers in full cooling position (2 not); All actuators disconnected from economizer dampers - 7 had them closed w/ return dampers	Two 20-year old 20kft2 army administration buildings, in NC
Seattle City Light (1997)	Broken damper linkage on cooling tower for refrigeration system - led to improper condenser water temperature control	Refrigeration system of 60kft2 grocery store in Utah
Seem and House (1999)	1 of 24 had an incorrectly installed electric damper actuator	New digital controllers installed for 24 dual-duct VAV boxes

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E.4 Airflow Not Balanced

Energy Impact Data

Table E-6: Energy Impact Data for Air Flow Not Balanced

Source	Key Information	Application Context
Fafard (2000)	A 5% savings in cfm circulated results in a 14% savings in fan horsepower	Did not provide information for reference
Liu et al. (1995)	137/210 (65%) of the terminal boxes had to be adjusted for air flow rate	Commissioning of a research building in Texas
Liu et al. (1996)	Total OA 25%> than design value due to poor balancing, with vary large units between four AHUS -39% to +99%; model suggests that this, along with improved cold and hot deck temperature reset schedules, would reduce cooling and heating energy by ~40%	99kft2 office building in Texas, retrocommissioning; central systems.
Liu et al. (2003)	Re-balancing could achieve a 40% reduction in ventilation, with ~25% reduction in steam, ~11% in chilled water; electric reduction unclear [all relative to post-commissioning values]	Simulation of a research building in Texas, ~123kft2; four single-duct CAV systems for ~93lft2, one dual-duct VAV systems for ~20kft^2 (library); rest for mechanical rooms
Luskay and Sellers (2002)	Poor balancing caused poor temperature control.	Renovated 11kft2 office space (one floor of building) to include underfloor air distribution
Seattle City Light (1997)	Spot-checks of balancing found "a number of significant discrepancies", "several areas were starved for air"	New 85kft2 new government office building, Portland, OR
Tennent and McKew (2000)	"Air system not balanced"; listed as "Past performance issue" in a campus context	50kft2 museum addition at Penn State
Tennent and McKew (2000)	HVAC control/balance issues; listed as "Past performance issue" in a campus context	83kft2 research/office building at Penn State
Wei et al. (2001)	Toilet and general exhaust systems unbalanced, causing isolation room pressure control problems	600kft2 9-story Minneapolis hospital

Table E-7: SBW Consulting (2003) Commissioning Observations of Air Flow Not Balanced

Key Information	Application Context
Numerous items not completed by balancing contractor; test and balancing spot check found many flows not passing	ID-ACC: New 340kft2 Idaho courthouse
VAV-28 - very low cfm (<20%), suspect tuning; VAV-8, some diffusers have low flow ~15 and 25% too low; VAV-31 - rebalance - some diffusers too high. A few boxes did not reach cooling CFM – VAV-11: 1,500/1,700 [actual/setpoint]; VAV-12: 792/1,100; VAV-13: 506/600; VAV-30: 5,549/6,800.	ID-BSU: New 90kft2 Idaho recreation center
Building Air Balance – Perform an air balance on the entire building after the remodel is completed and the VAV system is repaired and tuned - save 5,520kWh/year, 282 therms/year	ID-NAM: Retrocommissioning of a 23kft2 office building in Idaho
FTU-231, FTU-374, FTU-375: The measured primary CFM varies from the indicated BAS primary CFM by more than 20%.	MT-UMG: Retrocommissioning of a 110 kft^2 academic building

Commissioning found negative pressure in stairwells held open basement doors.	OR-CHS: New office building in Oregon, 160kft^2

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E.5 Insufficient Evaporator Airflow

Energy Impact Data

Table E-8: Energy Impact Data for Insufficient Evaporator Airflow

Source	Key Information	Application Context
Architectural Energy (2003)	39% of units had airflow <300 cfm/ton; average airflow of 325 cfm/ton	79 newly-installed small packaged RTUs in California

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[230] An energy management analyst for the City of Seattle notes that the studies were all completed in or before1997.

Source	Key Information	Application Context
Breuker and Braun (1998)	Laboratory measurements of a 3-ton unit with blower power varied to change airflow over cooling coil: • 12% reduction in flow: -6% in COP • 24% reduction: -12.3% in COP • 36% reduction: -17.4% in COP.	Laboratory tests for 3-ton RTU
Carl and Smilie (1992)	Monitoring commercial A/C systems in Louisiana indicated that evaporator coil cleaning is more important than changing filters.	Serviced 8 A/C systems in restaurants, 8 in grocery stores, and 7 in motels in Louisiana.
Davis et al. (2002)	Average cfm/ton of 304, ranged from 99 to 429; 4% savings in annual cooling energy for units with evaporator airflow problems *that could be fixed* (20% of all units)	27 commercial A/C units, mostly smaller (5-12.5 ton range), in California
Downey and Proctor (2002)	25% of commercial units considered to have “low airflow”(<350 cfm/ton compared to 400 cfm/ton level)	Measurements for 4,385 Californian light commercial A/C units – of which ~16% were between 5 and 20 tons; unclear how applicable statistics are to different size ranges
Fafard (2000)	Evaporator coils uncleaned for 18 month exhibit a 27% loss in heat transfer, cleaned coils show a 9% loss in heat transfer compared to new coils	
Hewett et al. (1992)	Wet coils had airflows ranging from 196 to 481 cfm/ton, mean = 334 (but airflow generally optimized as much as could be given ducts). Only 3 of 18 within +/- 10% of 400, ~9 within +/-20%. About 50% of cooling coils found to be “dirty or very dirty”.	18 systems with 25 compressor circuits in New England light commercial AC units; all at least 4 years old; comments on general maintenance; airflow almost never measured, coils rarely cleaned.
Houghton (1997)	Pleated filters better than flat filters; deeper filter racks better than shallow filter racks(3) replacing dirty filters showed a static pressure increase of 1in. of water gage (250 Pa) with a net decrease of 1% of energy cost, increasing air flow 23% and cooling capacity 7%	10-ton unit
Parker et al. (1997)	Decreased evaporator airflow from 425 cfm/ton reduces EER by: 359 cfm/ton – 2% 253 cfm/ton – 8% 218 cfm/ton – 12% 195 cfm/ton – 13.5% 127 cfm/ton – 27.5% Pleated filters reduce airflow by 5% relative to flat filters	Laboratory testing of a 7.04 EER *residential* unit, 2.55 tons
Rossi (2004)	13% of units had a low-side heat transfer problem, which includes insufficient evaporator airflow as well as poor evaporator heat transfer	1,468 different vapor compression circuits from commercial and residential unitary equipment at many locations throughout the U.S.; data collected by technicians using multi-sensor portable data acquisition system

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E.6 Software Programming Errors

Energy Impact Data

Table E-9: Energy Impact Data for Software Programming Errors

Source	Key Information	Application Context
Ardehali and Smith (2002)	Software programming accounted for 31% of the control-related problems.	Literature Review of Case Studies of Controls-Related Inefficiency: identified 384 control-related problems in more than 118 buildings and 67 reported case studies
Friedman et al. (2002)	4 had economizer control algorithm problems 3 had discharge air temperature reset problems 2 had simultaneous heating and cooling 3 had VFD modulation problems 2 had space temperature control problems	10 buildings commissioned (5 in CA, 5 in Pacific NW) between 1996-2000; other problems also noted
Haasl, T. et al. (2001)	(1) economizer algorithm was changed to use enthalpy instead of dew point to measure heat content,	(1) 3 office buildings in Massachusetts
Haasl, T. et al. (2001)	(2) fixed an "and" that should have been an "or" statement in the EMS program, 1% energy savings	(2) an office building in Portland, Oregon

Source	Key Information	Application Context
Haasl, T. et al. (2001)	(3) EMS night purge program parameters changed, 5% energy savings	(3) a retail facility in Colorado
Kjellman (1997)	>84 deficiencies found (multiple items of same deficiency counted as one) - 15% from incorrect or incomplete EMCS programming, e.g., no schedules or alarms	>100kft2 6-story city hall, commissioning of central plant retrofit
Kjellman (1997)	>50 deficiencies found (multiple items of same deficiency counted as one) - 26% from incorrect or incomplete EMCS programming, e.g.: chiller enabled before considering economizer, no warm-up schedule, CHW valves and economizer dampers in normally open position for all AHUs during unscheduled hours; minimum VFD set at 50% vs. 20% (for AHU)	Commissioning of 2-story elementary school HVAC system retrofit, ~35kft2; 6 multi-zone face and bypass CAV AHUs
Mazzucchi et al. (1997)	Morning warmup/cooldown supply air temperatures set based on zone calling for most heat/cooling, changed to average heat/cooling levels; CHW temp based on OS temp, changed to based on VAV valve position; economizers remained fully open-changed to accept minimum OA when OA temp exceeds return air temp	21-storey 100kft2 medical building in Seattle, commissioned after retrofit; Commissioning included: DDC control system, 3 AHUs, two VS pumps, VAV terminal units, water-side economizer
McCarthy et al. (2001)	Identified incorrectly calibrated DDC sensors and controls, poor DDC control sequence programming, would have caused over-heating and over-cooling; improper T-stat placement led to lack of temp control; no information on prevalence or energy impact.	20kft2 hospital cancer care unit, Boston
McCarthy et al. (2001)	Identified poor DDC control sequence programming for central AHU systems - caused multiple alarms and IAQ/smoke control problems; no information on prevalence or energy impact	45kft2 biomedical research lab in Boston hospital; all new HVAC systems
Seattle City Light (1997)	Supply air temperature reset controls not programmed; after programming, occasional cooling and heating resulted	New 85kft2 new government office building, Portland, OR
Thomas and Stum (1999)	Pre-heat coils came on during night purge sequence, heating rather than cooling space	

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E.7 Improper Controls Hardware Installation

Energy Impact Data

Table E-10: Energy Impact Data for Improper Controls Hardware Installation

Source	Key Information	Application Context
Anders and Bruder (1996)	One improper lighting circuit control did not shut down an exterior lighting circuit during day [unclear how many circuits total]; all 5 indoor light dimming controls did not work well due to insufficiently sensitive photosensor	Commissioning of new 130kft2 WalMart in Southern California – focus on lighting controls, HVAC and EMCS
Ardehali and Smith (2002)	"Communication" (i.e. improper wiring) and "Controller" (i.e. incorrect controller) Hardware accounted for 4.2% of the control-related problems	Literature Review of Case Studies of Controls-Related Inefficiency: identified 384 control-related problems in more than 118 buildings and 67 reported case studies
Caner 1(996)	3% (20/600) of the room temperature sensor wiring was found faulty	1 academic building in Washington state, no energy savings data included
Caner (1996)	13% (5/39) reheat coil valves had the action reversed	1 academic building in Washington state, no energy savings data included
Carcaterra et al. (1997)	Control systems incomplete	New 179kft2 [78kft2 office, ~99kft2 research] building in College Park, MD
Casault (1997)	Improperly indexed actuators on two AHUs (serving small archives space), causing them to fail closed [example of one of "a significant number of equipment failures"]	New 75kft2 library
Friedman et al. (2003)	3 Buildings (30%) had a sensor in the wrong place or incorrect wiring and instrumentation.	10 buildings commissioned (5 in CA, 5 in Pacific NW) between 1996-200
Fuhr (2003)	58% of the problems found are due to installation mistakes or problems	11 electrical commissioning projects
Goody et al. (2003)	37% of *all* economizers considered “failed” 10% of economizer problems due to	54 rooftop units in the Northwest – 65% had had economizer problems

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[231] An energy management analyst for the City of Seattle notes that the studies were all completed in or before1997.

Source	Key Information	Application Context
	installation or setup issues	
Haasl et al. (1996)	Poor lighting control zoning, wastes ~$2,500/year; no T-stat for electric maintenance room AC unit, wastes ~$460/year	250kft2 Tennessee office buildings, 11 years old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures
Henderson et al. (2000)	"Many" of the two-way valves not functioning as expected, "several" not closing as expected due to miswired valves, improper solenoid coils and stuck valves; fixing decreased VS pump power draw by ~25%; "almost all" of 4 monitored sites had wiring problems: malfunctioning time delay circuits, improper solenoid voltages, general wiring errors. [Assume almost all of 4 means 3 of 4]	Four sites including a school in Tennessee with a 400-ton geothermal heat pump with 120 "heat pumps".
Hydeman et al. (1999)	Magnetic flow meters placed too close to elbows and valves, compromising accuracy by unknown amount. Not clear if used for control or monitoring.	Very large campus (17,000 ton chilled water plant) in California
Khan et al. (2002)	13 of 15 economizers never connected, lacked thermostats for operation	California long-term care facility; 15 3-5 ton RTUs, 30kft2
Kjellman (1997)	>84 deficiencies found (multiple items of same deficiency counted as one), 41% from poor installation or performance of new equipment, e.g., both chillers had condenser and CHW flows opposite specifications	>100kft2 6-story city hall, commissioning of central plant retrofit
Kjellman (1997)	>50 deficiencies found (multiple items of same deficiency counted as one) - 22% from poor equipment installation (e.g., supply air t-sensor located in closed-off bypass deck)	Commissioning of 2-story elementary school HVAC system retrofit, ~35kft2; 6 multi-zone face and bypass CAV AHUs
Luskay and Sellers (2002)	Poorly placed temperature sensor in underfloor plenum led to low temperature measurements, increasing reheat energy consumption	New underfloor air distribution system with: 15kft2 office, 25kft2 training center, and 135kft2 distribution center
Mazzucchi et al. (1997)	Bldg. Static pressure sensors located on two floors at fans - poor location; VAV systems operating at 0-degree pitch in night cooldown and purge modes - ran fans w/o moving air	21-storey 100kft2 medical building in Seattle, commissioned after retrofit; Commissioning included: DDC control system, 3 AHUs, two VS pumps, VAV terminal units, water-side economizer
McCarthy et al. (2001)	Pressurization monitors not installed (but specified); no information on prevalence or energy impact. [Assume used to verify pressures preventing contamination of sensitive zones].	20kft2 hospital cancer care unit, Boston
Parks and Kellow (2000)	Number and location of OA temperature sensors (for economizer operation); duct static pressure sensor location	Four SMUD-area buildings; not broken down by building or frequency/# of buildings
Pratt et al. (2000)	Return and mixed air temperature sensors swapped in 1 AHU	6 AHUs in a large SF hotel; selected because of economizer usage and spaces served, NOT prior evidence of faults
Schexnayder et al. (1997)	Desiccant cooling system disabled - no humidity sensor; cooling tower piped backwards	Commissioning of 36kft2 remodel + 9kft2 new conference and education center in S. California, EnergyStar building; commissioning began w/ ~1 month left in construction
Seattle City Light (1997)	Contractor substituted 3-way for 2-way valves on chilled water coils, defeating reason for VSD pump	26kft2 toxic waste lab in Utah; only fume hood VAV system and variable flow pumping system commissioned
Seattle City Light (1997)	Improper wiring caused one locker room supply fan heat recovery system to be out of operation for 5 months	85kft2 health club in Oregon; water-loop HP (w/ EMCS), locker exhaust heat recovery and pool dehumidification HP commissioned
Seattle City Light (1997)	"All of the HP water flow control valves were mixed up", I.e., wrong sizes, causing many to shut down from high pressure conditions	85kft2 health club in Oregon; water-loop HP (w/ EMCS), locker exhaust heat recovery and pool dehumidification HP commissioned
Seattle City Light (1997)	Daylight controls improperly calibrated - perimeter lights failed to dim; stable control	New 85kft2 new government office building, Portland, OR

Source	Key Information	Application Context
	difficult due to unexpected dark carpets	
Seattle City Light (1997)	"Some" compressor rack temp sensors uninsulated and yielded incorrect control signals	Refrigeration system of 60kft2 grocery store in Utah
Tennent and McKew (2000)	Controls connected to wrong equipment; listed as "Past performance issue" in a campus context	Events center, 360,000ft2 at Penn State
Tennent and McKew (2000)	Fan coils incorrectly piped; listed as "Past performance issue" in a campus context	Existing 75,000ft2 education/research building at Penn State
Thomas and Stum (1999)	Chiller lacked isolation valves caused chillers to cycle off from low flow	New 560kft2, 16-story courthouse in Portland, OR; "Sample Commissioning Findings" Listed, states that "numerous" other problems identified and addressed without documentation

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E.8 Improper Controls Set Up or Commissioning

Energy Impact Data

Table E-11: Energy Impact Data for of Improper Controls Set Up or Commissioning

Source	Key Information	Application Context
Anders and Bruder (1996)	Lighting Control sequences not fine tuned - unclear impact; short cycling of evaporator; Condenser fan motors cycling between high and low due to incorrectly calibrated sump temperature sensors.	Commissioning of new 130kft2 WalMart in Southern California - focus on lighting controls, HVAC and EMCS
Architectural Energy (2003)	6% had simultaneous heating and cooling	140 newly-installed small packaged RTUs in California
Arney and Frey (1997)	Compressors energized in 3 of 4 units when system should be economizing. Supply air temp setpoints too low, causing excessive terminal heating; Supply VAV fans not modulating properly.	125kft2 building with 8 RTUs, 4 studied for two weeks (ONLY RTUs studied)
Butler (1997)	Frequent start-up of secondary chiller - EMCS setpoint adjustment saved ~$1,000/year *[0.3¢/sqft]*	958kft2 Honeywell corporate campus, 8 multi-story buildings, ~600 control points, Minneapolis
Caner (1996)	11/11 (100%) of the AHUs had a design error in the sequence of operations for preheat coils, fixing the error saved 30,000 therms/yr	1 academic building in Washington state, no information on total number of therms/yr consumed by the building
Claridge et al. (1994)	Dollar Energy savings $143K for Hot Deck/Cold Deck Reset Optimization *[119¢/sqft (17% energy cost)]*	Houston Medication School Facility (120ksf), before change energy cost $844K
Claridge et al. (2000a)	All OA preheated to above 100^{o}F due to high pre-heat setpoint; heating and cooling energy dropped after fixing by at least 33% and 22-50% *[33%+ heating energy, 22% to 50% cooling energy]*	165kft^{2} educational building (labs, offices, lecture halls) in College Station, TX; central AC
Courts (1999)	OS sensor (pneumatic) out of calibration by +6^{o}F, reducing use of economizer, $800 energy savings from fixing; electric duct heaters operating often in 60-70^{o}F OA temp range, re-programmed EMCS to "lockout" heaters appropriately, saved $3.7k/year *[0.3¢/sqft, 1.5¢/sqft]*	240kft2 office building in Portland, OR, 18 years old

Source	**Key Information**	**Application Context**
Davis et al. (2002)	3 of 22 economizers were set to OFF and would never provide cooling; 1 of 14 set at 40F; annual cooling savings estimated at 14 to 26% (for 55 and 60F changeover temperatures) *[14% to 26% cooling energy]*	23 packaged rooftop units, most CV, from 2.5-15 tons, several vintages, one split unit; Eugene, OR; savings based on Proctor (1990)
Eley Associates (2002)	For 24-hour operation, "No Reset" and "Reset by OA" strategies for supply air temperature increased total HVAC electricity consumption relative to "Reset by Warmest Zone" strategy[233]: Cooling – 101% / 50% [No Reset/Reset by OA] Pumps & Auxiliary – 11% / 6% Ventilation – 36% / [10%][234] Heating [gas] - ~3,000% / ~950% For a 5-day schedule, total HVAC electricity varied by ~10% with strategy used	DOE 2.2 S simulations of a $105kft^2$ office building in California with a VAV system
Energy Design Resources (1998)	5 of 11 EMCS installations not achieving desired savings, savings average 55% of intended for these 5, primarily due to intended control strategies not being implemented.	1995 survey of 11 New England Buildings
EPA (2001)	Typical savings associated with tuning controls can range up to 30% of energy costs	Re-commissioning chapter in Energy Star® Buildings Manual
Fish (1999)	RTU configured for CAV, VAV operation intended, many programmable settings not set properly (unclear what, impact)	5kft2 animal research and services bldg., Northwestern US (it appears; not certain)
Friedman (2003)	6 (60%) required scheduling to be implemented and 4 (40%) had economizers with faulty controls algorithms	10 buildings commissioned (5 in CA, 5 in Pacific NW) between 1996-200
Goody et al. (2003)	37% of *all* economizers considered "failed". Problem causes include: • 50% temperature changeover setting • 10% improper installation or setup	54 rooftop units in the Northwest – 65% had had economizer problems
Haasl and Edmunds (1997)	Improve economizer operation for 8 AHUs (save $742), add supply air reset for 2 AHUs (save $1,285/year), add CHW reset (save $946), reduce freeze protection setpoint to 35F ($6k/year), reduce chiller lockout setpoint to 60F (save $579) *[0.4¢/sqft, 0.7¢/sqft, 0.5¢/sqft, 0.3¢/sqft]*	175kft2 state office building, 7 stories, Tennessee, built in 1950 and 1970; built-up system, 19 AHUs, EMCS, 2-300 ton chillers, 418 under-window ventilators
Haasl et al. (1996)	Poor defrost schedules and enthalpy control, waste ~$1,025/year. *[1¢/sqft (0.4% energy cost)]*	107kft2 Massachusetts retail, 4 years old; propane furnace, DX RTUs, non-ducted CV air system, EMCS; ~$255k/year energy expenditures
Haasl et al. (1996)	Floating head pressure control not activated, waste ~$840/year; *[0.8¢/sqft (0.3% energy cost)]*	107kft2 Massachusetts retail, 4 years old; propane furnace, DX RTUs, non-ducted CV air system, EMCS; ~$255k/year energy expenditures
Haasl et al. (1996)	Suboptimal night purge and start control sequences, wasting ~$3,900/year; suboptimal stop control, wasting ~$1,075/year *[3.2¢/sqft, 0.9¢/sqft]*	122kft2 Colorado retail, 20 years old; natural gas boiler, 2 centrifugal chillers, multi-zone CV system, EMCS w/ pneumatics; ~$107k/year energy expenditures
Haasl et al. (1996)	Poor hot water pump lockout parameters, wastes ~$1,125/year *[0.5¢/sqft (0.3% energy cost)]]*	250kft2 Tennessee office buildings, 11 years old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures

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[233] For baseline case of 51°F supply air temperature.

[234] Denotes 10% decrease in ventilation electricity consumption.

Source	Key Information	Application Context
Haasl et al. (1996)	Low chiller water temperature setpoints, increasing saved ~$2,000/year; Poor duct heater control, improving saves ~$5,300/year *[0.7¢/sqft (0.8% energy cost), 1.9¢/sqft (2.1% energy cost)]*	278kft2 Oregon office building, 17 years old; electric duct heaters, 2 centrifugal chillers, VAV (variable-pitch) system; EMCS w/ pneumatics; $248k in energy expenditures/year
Haasl, T. et al 2001	Implemented a reset strategy for the duct static pressure setpoint, 1% energy savings	3 office buildings in Massachusetts,
Henderson et al. (2000)	Excess differential pressure setpoint for variable-speed ground loop water systems caused roughly doubling of pump power.	Water-source heat pump installations with VS pumps: (1) 2711ft2 fast food restaurant, near Detroit (2) 188kft2 retail in OK
Hill et al. (2000)	"Over-cooling , which required re-heating" - mentions "adjusting various air handling system, chiller, and boiler controls ... Start/stop times, reset temperatures and pressures, calibration, and optimum use of equipment"; considered no/low-cost measures	108,000ft2 Chicago office building
Kessler et al. (1996)	During re-calibration of cooling tower controls, faulty valve identified (problem unclear)	623kft2 Chicago office building, audit of 640 fan-powered boxes
Liu et al. (1993a)	Energy savings estimates for Hot Deck/Cold Deck Reset Optimization: 34% of 22,300 MMBtu CHW use (save $55,700), 26% of 13,700 MMBtu Steam use (save $18,000). Primarily eliminate simultaneous heating and cooling, slight humidity increase modeled for summer, but within 60%RH. *[59¢/sqft (77kBtuh/sqft primary energy[1,2,3])]*	Clinical Science Building (125ksf) six story facility part of University of Texas Medical Branch in Galveston Texas. Served by single Dual-Duct unit. [Baseline primary energy use for HVAC not including electricity for blowers, fans, pumps 260kBtuh/sqft[1,2,3]]
Liu et al. (1993b)	Energy savings estimates for Hot Deck/Cold Deck Reset Optimization: 22% of 76,800 MMBtu CHW use (save $124,500), 37% of 26,800 MMBtu Steam use (save $50,100). Primarily eliminate simultaneous heating and cooling. *[47¢/sqft (64kBtuh/sqft primary energy[1,2])]*	John Sealy South Building (373ksf) twelve story facility part of University of Texas Medical Branch in Galveston Texas. Served by four dual-duct units [Baseline primary energy use for HVAC not including electricity for blowers, fans, pumps 231kBtuh/sqft[1,2,3]]
Liu et al. (1993c)	Energy savings estimates for Hot Deck/Cold Deck Reset Optimization: 24% of 15,700 MMBtu CHW use (save $27,700), 43% of 8,700 MMBtu Steam use (save $18,800). Primarily eliminate simultaneous heating and cooling. *[69¢/sqft (108kBtuh/sqft primary energy[1,2,3])]*	Moody Library Building (67ksf) six story facility part of University of Texas Medical Branch in Galveston Texas. Served by two Dual-Duct units with cold deck upstream of the blower. [Baseline primary energy use for HVAC not including electricity for blowers, fans, pumps 323kBtuh/sqft[1,2,3]]
Liu et al. (1993c)	Energy savings estimates for Economizer Operation Optimization: 24% of 15,700 MMBtu CHW use (save $28,100). *[42¢/sqft (39kBtuh/sqft primary energy[1,2])]*	Moody Library Building (67ksf) six story facility part of University of Texas Medical Branch in Galveston Texas. Served by two Dual-Duct units with cold deck upstream of the blower.
Liu et al. (1994a)	Total energy savings estimates for reduction of boiler pressure from 145 to 125psig for boilers serving 49 buildings: 7% of 437,600 MCF gas use (save $82,000). Savings result from annual average boiler efficiency boost from ~67% to ~72%. *[2.4¢/sqft (9kBtuh/sqft primary energy)]*	University of Texas Medical Branch in Galveston Texas (total floor area 3,354ksf); Buildings in which savings occur served by Dual-Duct units. [Baseline primary energy use for HVAC not including electricity for blowers, fans, pumps 298kBtuh/ft^2; see Table Notes 1,2 and 3]
Liu et al. (1994a)	Total energy savings estimates for optimization of chiller plant operation, including LCHWT reset with OAT and ECWT schedule optimization: 22% of 69,711,000kWh (save $852,000). *[25¢/sqft (50kBtuh/sqft primary energy[2])]*	University of Texas Medical Branch in Galveston Texas (total floor area 3,354ksf). Buildings in which savings occur served by Dual-Duct units. [Baseline primary energy use for HVAC not including electricity for blowers, fans, pumps 298kBtuh/ft^2; see Table Notes 1,2 and 3]

Source	**Key Information**	**Application Context**
Liu et al. (1994a)	Total energy savings estimates for Optimized Hot Deck/Cold Deck Schedules in 39 of 49 buildings: 15% to 21% of 906,500 MMBtu CHW use (save $1,336,000); 33% to 44% of 301,300 MMBtu steam use (save $600,000). Percentages and baseline use for all 49 buildings. Range of savings due to uncertainty of modeling: Authors claim that baseline metering deviation from modeling can be claimed as potential savings. *[58¢/sqft (77kBtuh/sqft primary energy[1,2,3])]*	University of Texas Medical Branch in Galveston Texas (total floor area 3,354ksf). Buildings in which savings occur served by Dual-Duct units. [Baseline primary energy use for HVAC not including electricity for blowers, fans, pumps 298kBtuh/ft^2; see Table Notes 1,2 and 3]
Liu et al. (1996)	Cold deck temperature reset subpar, led to simultaneous heating and cooling; model suggests that this, along with reduced OA flow rates, would reduce cooling and heating energy by ~40%	99kft2 office building in Texas, retrocommissioning; IAQ problems identified ~13 years earlier; central systems
Mazzucchi et al. (1997)	Warmup/cooldown period sequenced with 1-hour minimum run period, leading to extra fan runtime when not needed; vane axial relief fan minimum blade position that over-pressurized discharge plenum; one pump VFD did not go below 85% - reprogrammed to 20% minimum; chiller cycling due to negligible economizer dead band - 4F dead band fixed problem; simultaneous heat & cool between perimeter (cooling) and core (heating) – fixed; 4F chilled water reset increment - changed to 1F	21-storey 100kft2 medical building in Seattle, commissioned after retrofit; Commissioning included: DDC control system, 3 AHUs, two VS pumps, VAV terminal units, water-side economizer
Mazzucchi et al. (1997)	5 Issues: (1) Common relief dampers did not open when needed due to "problem" with pneumatic output signal; (2) Induction unit OA and return dampers out of adjustment, starving fan--fixed by re-adjusting positioner; (3) one return damper did not open fully due to incorrect pressure reading; (4) One control valve did not close during waterside economizer operation - transducer issue; (5) overcooling due to 50F versus 75F intended induction air temperature	21-storey 100kft2 medical building in Seattle, commissioned after retrofit; Commissioning included: DDC control system, 3 AHUs, two VS pumps, VAV terminal units, water-side economizer
Mazzucchi et al. (1997)	warm up cycle sometimes ineffective - 8th floor PRV stuck at 2.5psi - reset to 9psi	21-storey 100kft2 medical building in Seattle, commissioned after retrofit; Commissioning included: DDC control system, 3 AHUs, two VS pumps, VAV terminal units, water-side economizer
McCarthy et al. (2001)	Identified incorrectly calibrated DDC sensors and controls, poor VAV control of central AHU, caused fan shutdown, higher flow rate than needed; no information on prevalence or energy impact	Boston hospital emergency ward renovation, 21k ft2
Piette et al. (1994)	Changing the control method to reset cool supply air resulted in an annual savings estimate of 142.5 MWh/yr of electricity and 509 therms/yr of gas	Case study of an office building in Oregon
Piette et al. (1994)	Incorrect control settings were responsible for a total of 26.6 MWh/yr of electricity and 80 therms/yr of gas	Case study of an office building in Utah
Piette et al. (2001)	Poor chiller sequencing results in significant chiller cycling during day and at night (e.g., 5 minute cycle at night)	Continuous monitoring of EMCS data from two office towers in Oakland, 971k ft2 office space, 7.2k computer center; 5 chillers; won Energy Star Label without major retrofits
Pratt et al. (2000)	1 outdoor air economizer (OAE) improperly set up [improper description of control scheme or setpoint value]	6 AHUs in a large SF hotel; selected because of economizer usage and spaces served, NOT prior evidence of faults

Source	Key Information	Application Context
Santos and Rutt (2001)	25 sensor "anomalies" found: 3 due to improper sensor characterization during configuration; 2 occupancy-based anomalies found.	PACRAT AFDD applied during a 6-month period to 8 AHUS (230,000cfm total) at a pharma campus in the Midwest
Schexnayder et al. (1997)	Improper desiccant cooling system control sequence, 2 of 4 VAV AHUs not converted to VAV operation	Commissioning of 36kft2 remodel + 9kft2 new conference and education center in S. California, Energy Star building; commissioning began w/ ~1 month left in construction
Seattle City Light (1997)	Improper static pressure setpoint for supply air fans - VSDs ran at full speed all the time; same problem for the pumping system; controls deficiency drove two secondary pumps at very different speeds	26kft2 toxic waste lab in Utah; only fume hood VAV system and variable flow pumping system commissioned
Seattle City Light (1997)	Aerobics room: 63F cooling setpoint, 61F heating setpoint, caused excessive cooling and simultaneous heating/cooling.	85kft2 health club in Oregon; water-loop HP (w/ EMCS), locker exhaust heat recovery and pool dehumidification HP commissioned
Seattle City Light (1997)	Incorrect EMCS setpoint resulted in terminal unit reheat fans not coming on when heat needed	New 85kft2 new government office building, Portland, OR
Seattle City Light (1997)	Refrigeration compressor head pressure not allowed to float below 90F, although ~75F seen feasible – energy waste	Refrigeration system of 60kft2 grocery store in Utah
Thomas and Stum (1999)	CHW reset disabled	New 560kft2, 16-story courthouse in Portland, OR; "Sample Commissioning Findings" Listed, states that "numerous" other problems identified and addressed without documentation
Wei et al. (2001)	Measured AHU discharge temperatures varied from 45-55F, poor AHU reset schedule; all 12 VAV AHUs had constant duct pressure setpoints; improper economizer setpoint in the 70-75F range; only manual control of chiller plant and hydronic hot water pump; toilet and general exhaust systems unbalanced; bad thermostats found; some AHUs took in too much OA; some leaky reheat valves. Total building savings for all fixes ~5% of electricity, ~ 23% of steam.	600,000ft2 9-story Minneapolis hospital
Zhu et al. (1997)	Improved reset temperatures for 21 dual duct VAV AHUs w/ VAV boxes that serve ~60% of floorspace	360kft2 (conditioned space) office building in Austin, TX, built in 1992

Notes

[1] Assumes a seasonal chiller efficiency of 0.75kW/ton.

[2] Assumes a primary energy utilization for electricity production of 11,000Btu/kWh.

[3] Assumes a boiler efficiency for steam generation of 80%.

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E.9 Control Component Failure or Degradation

Energy Impact Data

Table E-12: Energy Impact Data for Control Component Failure or Degradation

Source	Key Information	Application Context
Ardehali and Smith, 2002	"Input device" (i.e. broken sensor/thermostat) accounted for 15.9% of control-related problems	Literature Review of Case Studies of Controls-Related Inefficiency: identified 384 control-related problems in more than 118 buildings and 67 reported case studies
Butler (1997)	Broken photocell cause South outdoor dock lights to operate all day; repair of photocell saved ~$40/year *[negligible ¢/ft^2 savings]*	958kft2 Honeywell corporate campus, 8 multi-story buildings, ~600 control points, Minneapolis
Casault (1997)	DDC field panel circuit board fails during testing [example of one of "a significant number of equipment failures"]	New 75kft2 library
Claridge et al, 1994	Dollar Energy savings $111K for sensor calibration which resulted in cold deck operating 2 to 4 degrees low. *[92¢/ft^2]*	Houston Medication School Facility (120ksf), before change energy cost $844K
Claridge et al. (1996)	"Several" heating and cooling coil T-stats need replacement or re-calibration, valves needed controllers; together, expected to save $133,600/year *[6.7¢/ft^2 based on floor area of all eight buildings]*	One of Eight government office buildings in Austin, TX, ranging from 80,000 to 491,000ft2, totaling ~2,000,000ft2;

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[235] An energy management analyst for the City of Seattle notes that the studies were all completed in or before1997.

Source	**Key Information**	**Application Context**
Courts (1999)	EMCS failure caused CHWS temperature cut-in/cut-out setpoints to revert to default 52/48 from desired 56/53 - ~8% COP increase	240kft2 office building in Portland, OR, 18 years old
Davis et al. (2002a)	Of 15 dry bulb-linked economizers, 7 had no setpoints recorded (3 of these had broken microswitches - economizers inoperable; 1 had functional damper that went to full open when compressor came on); 3 of the 8 units with setpoints had the economizer set to "off", 1 of 8 set to 40°F	23 packaged rooftop units, most CV, from 2.5-15 tons, several vintages, one split unit; Eugene, OR
Davis et al. (2002b)	Over 50% of economizers had at least one serious fault, bad temperature sensors the most common	Based on "small samples" from Lunnenberg (1999) and Davis Energy Group (2001)
Friedman et al. (2002)	5 (50%) had chiller control problems 5 (50%) had hydronic control problems 4 (40%) had sensor problems	10 buildings commissioned (5 in CA, 5 in Pacific NW) between 1996-2000; other problems also noted
Goody et al. (2003)	37% of *all* economizers considered "failed" Breakdown of Economizer Problems includes [percentages of units *with* problems]: 5% - Actuator / controller 10% - Outdoor air sensor 5% - Seized damper 5% - No power 2% - Non-functioning linkage	54 rooftop units in the Northwest – 65% had had economizer problems
Haasl et al. (1996)	Return CHW pump VFD not operating, wastes ~$7,300/year *[2.9¢/ft (1.6% energy cost)]*	250kft2 Tennessee office buildings, 11 years old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures
Haasl et al. (1996)	Pneumatic OA sensor out of calibration; fixing saved ~$800/year *[0.3¢/ft^2 (0.3% energy cost)]*	278kft2 Oregon office building, 17 years old; electric duct heaters, 2 centrifugal chillers, VAV (variable-pitch) system; EMCS w/ pneumatics; $248k in energy expenditures/year
Hydeman et al. (1999)	"Many" controlled devices had deficiencies - several valves, valve actuators and/or positioners, and chiller controllers were replaced; chiller staging anti-recycle timers (delays) too great, plant would get out of control before starting new chiller(s); many other chiller plant and condenser water control issues.	Very large campus (17,000 ton chilled water plant) in California
Kjellman et al. (1995)	100% of the thermostats sampled were out of calibration (5-10% of the thermostats were sampled)	a study of 7 buildings in S. California
Kjellman et al. (1995)	Enthalpy sensors in 70% (5/7) of the buildings needed replacement	a study of 7 buildings in S. California
Liu et al. (1995)	122/210 (58%) of the terminal boxes had valves that leaked	a research building in Texas
Liu et al. (2003)	Preheat deck temperature sensor out of calibration (3-5°C lower than measured); pneumatic actuator lines for chilled water valves leaked, always more than half open => simultaneous heating and cooling; chilled water utility meter by-pass valve open => chilled water data 50% low; Net effect:63% annual reduction in heating, 42% in cooling	A research building in Texas, ~123kft2; four single-duct CAV systems for ~93lft2, one dual-duct VAV systems for ~20kft^2 (library); rest for mechanical rooms
Nichols and Glass (1999)	"Several" supply fan inlet vanes slipping, three did not open at all [unclear total number of units]	440kft2 new and 170kft2 renovated medical facility; Seattle
PECI (1997b)	Sensors not working properly in 1/3 of buildings	Study of 60 Commercial Buildings
Piette et al. (1994)	A VAV box valve stuck open was responsible for a total of 5 MWh/yr of electricity and 300 therms/yr of gas	Case study of an office building in Utah

Source	Key Information	Application Context
Piette et al. (1994)	Failed control components were responsible for a total of 9.3 MWh/yr of electricity and 900 therms/yr of gas	Case study of an office building in Utah
Pratt et al. (2000)	2 AHU Temperature sensors failed	6 AHUs in a large SF hotel; selected because of economizer usage and spaces served, NOT prior evidence of faults
Rojeski and Groover (1999)	0 of 8 AHUs had operational T-stats and control systems; 2 of 8 multizone AC units had non-operating T-stats; "discriminator controls in each control panel were disconnected, pressure gauges read zero.	Two 20-year old 20kft2 army administration buildings, in NC
Schexnayder et al. (1997)	1 of 4 AHU disabled for VAV operation due to static pressure sensor problems	Commissioning of 36kft2 remodel + 9kft2 new conference and education center in S. California, EnergyStar building; commissioning began w/ ~1 month left in construction
Seattle City Light (1997)	Return air temp sensors out of calibration by 5 to 18F for all racquetball courts, increased compressor cycling; failed controller for lower lobby, causing heating when hot, cooling when cool; OA temp and humidity sensors for pool failed; simultaneous heating and cooling - "battle" between two HPs; one HP compressor failed.	85kft2 health club in Oregon; water-loop HP (w/ EMCS), locker exhaust heat recovery and pool dehumidification HP commissioned
Seattle City Light (1997)	T-stat for one zone faulty; failed electric components in one perimeter VAV box	New 85kft^2 new government office building, Portland, OR
Seattle City Light (1997)	Store humidity sensor "badly" out of calibration - excess refrigeration;	Refrigeration system of 60kft2 grocery store in Utah
Tennent and McKew (2000)	Chilled water controls not functioning properly - unclear if programming, setup or degradation issue; listed as "Past performance issue" in a campus context	~new buildings, 57kft^2 research building at Penn State
Wei et al. (2001)	"Some" AHU flow measurements off by up to 50%, many failed RH sensors - unclear prevalence for both; 3 of 5 VAVs with inlet guide vanes were frozen in partially closed positions, apparently due to lack of maintenance; VAV boxes out of calibration (more than 1000) impacting controllable range, unclear why.	600kft^2 9-story Minneapolis hospital

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E.10 Valve Leakage

Energy Impact Data

Table E-13: Energy Impact Data for Valve Leakage

Source	Key Information	Application Context
Bjorklund et al. (2003)	A leaking steam valve was found to cost 132,300 kWh per year of energy (no data on total energy use of building)	A commissioning study of a new biomedical research building in Connecticut
Butler (1997)	Over 400 defective steam traps – repair saved $27.6k/year	958kft2 Honeywell corporate campus, 8 multi-story buildings, ~600 control points, Minneapolis
Caner (1996)	10% (6/59) of the steam valves in the AHUs did not close properly, accounting for 21,000 therms/yr and 82,000 kWh/yr of energy wasted	One academic building in Washington state, no information on total number of therms/yr or kWh/yr consumed by the building
Caner (1997)	A "high rate" of failure among 56 steam valve extensions prevented full closure of steam valves	Commissioning of 4 academic buildings in Washington
Carcaterra et al. (1997)	Debris in VAV reheat piping system caused 2-way valve to stick, "hundreds" of rooms to be overcooled – fixed	New 179kft2 [78kft2 office, ~99kft2 research] building in College Park, MD
Haasl et al. (1996)	Chilled water coil valve leaking, wasting	250kft2 Tennessee office buildings, 11 years

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[236] An energy management analyst for the City of Seattle notes that the studies were all completed in or before1997.

	~$17k/year	old; district steam and chilled water; VAV (inlet vanes) system; EMCS w/ pneumatics; $450k in annual energy expenditures
Henderson et al. (2000)	No valve problems reported over two-year period	New York hotel with geothermal heat pump w/ VS pump
Wei et al. (2001)	Leaky reheat control valves repaired (unclear prevalence and impact)	600,000sqft 9-story Minneapolis hospital

Table E-14: SBW Consulting Commissioning Observations of Valve Leakage

Key Information	Application Context
Possible leaking heating valve or sensor calibration problem on VAV-28 and VAV-40; Possible leaking cooling valve or sensor calibration problem on VAV-26 and VAV-32; Possible cooling valve problem (leakage or reversed of valve position) on VAV-10, -20, -35. With both valves closed and heating system inactive/ cooling active	ID-BSU: New 90kft2 Idaho recreation center
Control valve in RP-2 in Room 172 is leaking through; RVV-4: The heating valve is not fully closing or is leaking through (note: total of at least 13 RVVs)	MO-AAS: Retrocommissioning of 56kft2 maintenance facility in Montana
The heating valve is not fully shut at 100% signal	MT-EVM: Retrocommissioning of Montana middle school, 64,000sf
The hot water heating coil valve does not close properly	MT-UMG: Retrocommissioning of U of Montana academic building, 110,000sf
Steam pressure relief valves SC-03 [Assume leaking]	WA-OCH: New hospital in Washington, 51,000sf
Pressure relief valves CW-07/HW-03 [Assume leaking]	WA-SCC: New academic building in Washington, 60,000sf

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E.11 Fouled Air-Cooled Condensers

Energy Impact Data

Table E-15: Energy Impact Data for Fouled Air-Cooled Condensers

Source	Key Information	Application Context
Breuker and Braun (1998a)	Laboratory measurements of physical area airflow blockage percentage and COP/capacity degradation 14% blockage – 4.3% / 3.1% 28% blockage – 7.7% / 4.8% 42% blockage – 12.2% / 7.4% 56% blockage – 17.9% / 10.9%	Laboratory tests for 3-ton RTU
Carl and Smilie (1992)	Monitoring commercial a/c systems in Louisiana indicated that periodic condenser coil cleaning is needed in restaurants and grocery stores, less so in motels.	8 a/c systems in restaurants, 8 in grocery stores, and 7 in motels. Comprehensive servicing of a/c system produces energy savings from 14 to 28%.
Davis et al. (2002)	2 of 14 units had "dirty coils" that initially prevented proper estimation of refrigerant charge levels; estimated 6% annual cooling energy reduction from fixing condenser coils, 5% of units could be improved by condenser cleaning.	14 packaged rooftop units from 2.5-15 tons, several vintages, one split unit; Eugene, OR; savings based on Proctor (1990)
Goody et al. (2003)	~5% of units had dirty condenser coils that measurably degraded performance ~5% had insufficient condenser coil airlfow that measurably degraded performance	70 refrigerant circuits in 59 RTUs in the Pacific Northwest; condenser coil problems determined from 47 circuits
Hewett et al. (1992)	No systems had *visibly* dirty condenser coils.	18 systems with 25 compressor circuits in New England light commercial AC units; all at least 4 years old; comments on general maintenance; airflow almost never measured, coils rarely cleaned.
Houghton (1997)	Dirty condenser coils that raise the condensing temperature from 95°F to 105°F will cut cooling capacity by 7% and increase power consumption by 10%. Net efficiency reduction of 16%, increasing 10-ton unit operating costs by $250/year (for 2,000 hours annual operation).	Assumes that 75% of energy goes to the compressor and total energy costs of $0.08/kWh
Rossi (2004)	Almost 6% of circuits had condenser heat transfer problems	1,468 different vapor compression circuits from commercial and residential unitary equipment at many locations throughout the U.S.; data collected by technicians using multi-sensor portable data acquisition system

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E.12 Improper Refrigerant Charge

Energy Impact Data

Table E-16: Energy Impact Data for Improper Refrigerant Charge

Source	Key Information	Application Context
Breuker and Braun (1998a)	The following charge levels decreased COP and capacity by: 96.5% - 2.7% / 3.0% [COP/capacity decrease] 93% - 2.8% / 3.8% 89.5% - 3.6% / 5.6% 86% 4.6% / 8.0%	Laboratory tests for 3-ton RTU
Brownell et al. (1999)	In one of two refrigeration loops, low refrigerant charge due to leak in diaphragm of head pressure controller decreased performance by ~33% - energy penalty of ~$7.8k/year (@$0.047/kWh); leakage percentage not stated, 135pounds added	Indoor skating area with 25kft2 ice, in Madison, WI
Carl and Smilie (1992)	50%, 37%, 57% of the three types were serviced for improper refrigerant charge	Servicing of 8 A/C systems in restaurants, 8 in grocery stores, and 7 in motels in Louisiana
Davis et al. (2002)	5 of 14 units overcharged by an average of 8oz; 4 of 14 undercharged: one by 3 pounds (severe leak in pressure controller) [20% undercharge, 11% savings], one by 20 oz [10% undercharge, 6% savings], and 2 <6oz [charge deemed OK by service personnel]	14 RTUs, most CV, from 2.5-15 tons, several vintages, one split units; Eugene, OR; savings based on Proctor (1990)

Source	Key Information	Application Context
Downey and Proctor (2002)	~60% of commercial units in need of charge repair (>+/-5%); shows distribution curve based on 316 units (charge state distribution), but states that many contractors corrected charge before measuring charge	Measurements for 4,385 Californian light commercial A/C units - of which ~16% were between 5 and 20 tons; unclear how applicable statistics are to different size ranges
Farzad and O'Neal (1993)	Capillary tube systems showed that the following charge levels resulted in the following decreases in EER / SEER / capacity[237]: 120% - 14% / 12% / 13% 115% - 12% /10% / 11% 110% - 10% / 9% / 8% 105% - 6% / 5% / 6% 95% - (1%)[238] / 7% / 1% 90% - 1% / 11% / 5% 85% - 10% / 17% / 14% 80% - 16% / 21% / 23% TXV systems maintained all performance parameters to a much greater degree than capillary tube devices, particularly at lower charge levels	Laboratory tests of a 3-ton split-system residential A/C unit; capillary tube performed at ~9.8EER, the TXV at ~9.5EER The indoor enthalpy and refrigerant enthalpy cooling capacity measurements produced capacity values within +/-5% of each other.
Gage and Troy (1998)	25% of the supermarkets had refrigerant losses exceeding 20% of the charge per year, the average loss rate across all supermarkets was 14%; doesn't clearly have significant energy impact, due to system maintenance	36 supermarkets in southern California
Goody et al. (2003)	57% of refrigerant circuits studied had improper charge; undercharge about twice as common as overcharge	70 refrigerant circuits in 59 RTUs in the Pacific Northwest; undercharge/overcharge breakdown determined from 47 circuits
Goswami et al. (2001)	Low charge levels caused the following COP and capacity degradations: • 90% – 2% / 3.5% [COP/capacity] • 85% – 56% / Unclear • 80% - ~20% / >100% Recommends using air enthalpy method to evaluate performance at low charge levels; cycle cooling can create an ice layer that absorbs "cooling" but does not transfer appreciable heat to air	Laboratory testing of a 3-ton residential split A/C unit that uses R-22; tested per ARI 210 and ASHRAE Standard 37-1988.
Hewett et al. (1992)	Charge added to 8 (one empty; up to +123% added to others); charge removed from 10 (up to –41%); 7 approximately OK	18 systems with 25 compressor circuits in New England light commercial A/C units; all at least 4 years old
Hoover (2001)	75% of systems had less than 85% of design charge	Random survey in Florida of 22 A/C units in offices, fast food restaurant and a residence; capacities ranged from 3 to 10 tons

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[237] Capacity at 95°F outdoor temperature.

[238] The negative number indicates that EER increased by 1%.

Source	Key Information	Application Context
Houghton (1997)	A survey of 25 refrigerant circuits in 18 rooftop units found 72% (18) were improperly charged	No other information
Jacobs et al. (2003)	33 (46%) had improper charge levels (superheat or subcooling temperatures off by >5°F), increasing average annual cooling energy by 5%. Charge Frequency Distribution: • ~135% – 1 unit • ~125% – 1 unit • ~120% – 2 units • ~110% – 3 units • ~105% – 2 units • ~95% – 11 units • ~90% – 3 units • ~80% – 1 unit • ~75% – 1 unit • "Dog"[239] – 6 units	Evaluation of 74 refrigerant systems from 215 RTUs (in 75 newly constructed buildings in California) Energy impact based on Farazad and O'Neal (1993)
Kjellman (1997)	One of two chillers undercharged (operating at 0.92Kw/ton versus rating of 0.65kW/ton)	>100kft^2 6-story city hall - central plant retrofit with two 200-ton screw chillers
Kjellman et al. (1995)	Refrigerant leaks in 57% (4/7) of the buildings were found; study does not indicate charge levels and energy impact (if any)	Study of 7 buildings in S. California
Modera and Proctor (2002)	>60% of units with incorrect charge, with an average EER degradation of 12%; approximate charge frequency distributions[240] and EER impacts[241]: >=40%: 2% / -11% [Frequ. / EER impact] +30%: 2% / -4% +20%: 8% / 0% +10%: 17% / +1% -10%: 13% / -10% -20%: 10% / -23% -30%: 5% / -44% -40%: 3% / -74% >=-50%: 3% / ~little function	368 light commercial A/C systems in Southern California
Rossi (2004)	37% of circuits had incorrect charge levels; under-charge ~15-times more common than over-charge	1,468 different vapor compression circuits from commercial and residential unitary equipment at many locations throughout the U.S.; data collected by technicians using multi-sensor portable data acquisition system

References

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[239] Presumably very low levels of charge that result in dramatic capacity reduction.

[240] Approximate values estimated from bar graph; hence, uncertainties greater for smaller percentages.

[241] Based on Modera and Proctor (2002) curve fit for EER impact of refrigerant charge for short-tube units:

$$\text{EER (actual)} / \text{EER (rated)} = 5.08 - 4.10*[\%\text{Charge}] + 4.62*\text{LN}[\%\text{Charge}] .$$

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