Beyond Commissioning

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ABSTRACT

The emerging practice of commissioning when applied to existing buildings generally provides energy savings of 10% to, in some cases, more than 60% of a building's energy consumption. Moreover, commissioning ensures that equipment and systems are installed and operate properly, providing occupants with the conditions expected. Without commissioning, new buildings can have incorrect equipment installed, devices like fans installed backwards, and unimplemented control algorithms to mention a few deficiencies sometimes found. Existing buildings can have faulty and failed equipment such as clogged filters and coils, stuck dampers, leaky valves, and imbalanced air distribution, as well as overridden controls, improper set points, and incorrect schedules. Commissioning of new and existing buildings helps prevent and alleviate such problems. Yet only a small fraction of commercial buildings has ever been commissioned, and many buildings that have been commissioned have only a fraction of the recommended actions implemented. Time may change this situation or maybe other changes can accelerate the progress of commissioning.

Will commissioning continue in the future as it is performed today or must it change? The authors share a vision for 20 or 30 years from now for how the functions provided by commissioning could change. The paper delves into the roles of automation technology for functional testing, diagnostics, prognostics, correction of problems, data management, design review, and project management in building commissioning. The authors suggest that these technologies will change the practice of commissioning, increase its beneficial impacts—building performance, lower energy consumption, managed peak power use, and occupant satisfaction—and help accelerate its adoption by the commercial buildings sector by reducing the cost of commissioning while increasing its quality and persistence.

Introduction

Building commissioning has been described and promoted in a number of publications (Haasl and Sharp 1999; PECI 1997 and 2000; U.S. DOE and U.S. GSA 1998; U.S. DOE 2002; Claridge et al. 2000; Liu et al. 2002 and 2003). The term "commissioning" is commonly used to refer specifically to commissioning of buildings that are presently in the process of design and construction, new buildings, while "retrocommissioning" commonly refers to commissioning of existing buildings. The major differences in the two processes are that: 1) commissioning of new construction provides the opportunity to influence design, something that is not possible for retrocommissioning of existing buildings, except for major renovations or when significant equipment retrofits are made, because the building already exists, 2) retrocommissioning requires uncovering design information and verifying it where it even exists and characterizing the building and systems where as-built design information is not available or is inaccurate, and 3) commissioning involves verifying that the correct systems and equipment specified in the design are procured and then installed properly by contractors, whereas only proper installation can be verified normally in retrocommissioning.

The purpose of commissioning for new construction is captured well by U.S. DOE and U.S. GSA 1998 (p. 6) as "achieving, verifying, and documenting that the performance of a building and its various systems meet design intent and the owner's and occupants' operational needs. The process ideally extends through all phases of a project, from concept to occupancy and operation."

Problems found in commissioning and retrocommissioning include but are not limited to:

1. incorrectly installed equipment (e.g., backwards fans)
2. incorrectly implemented control algorithms (e.g., economizing cycles)
3. inefficient set points
4. unexpected equipment and lighting schedules that waste energy
5. missing and uncalibrated sensors

Some additional problems found specifically during commissioning of new construction include:

1. design decisions not consistent with stated design intent
2. equipment other than that specified delivered to the construction site for installation
3. incorrect or incorrectly-sized equipment installed

When executed effectively, preventing and correcting such problems, commissioning and retrocommissioning provide energy savings, monetary savings on energy and peak electric demand, extended equipment life, and greater occupant comfort and satisfaction with other indoor conditions. Energy savings reported for commissioning of existing buildings range from a few percent to over 60% with most reported savings in the range of 10% to 30% (U.S. DOE undated; Haasl and Sharp 1999; Claridge et al. 2000; and Liu et al. 2002).

Despite all the benefits, commissioning comes at a cost. A recent report (Quantum Consulting 2003, pp. 1-3) on commissioning in public buildings states "While the concept of commissioning is increasingly accepted, there are still barriers--particularly with regard to cost--to implementation of the kind of thorough, independent third-party commissioning that is necessary for the full benefits of commissioning to be realized." Only a small fraction of new construction and a very small fraction of existing buildings have been commissioned. Even when performed, pressures exist to keep costs down, which in some cases limits the depth to which the commissioning is performed. The authors hypothesize that costs play an important role in limiting the diffusion of commissioning into the building stock. Replacements or supplements to commissioning that reduce cost could in the long run better promote the objectives of commissioning. Key to this is reducing the labor intensity of commissioning by automating as many of the processes involved as possible. Compared to the cost of labor, automation technology is inexpensive.

Hypothesis – There's a Better Way

Commissioning provides important benefits to both new and existing buildings, but there may be a better way to achieve these benefits. In the long-term future (say 20 or 30 years from now), most (but not all) of the objectives of commissioning could be provided using automated processes, reducing many of the barriers that exist today for commissioning and impacting a much larger portion of the building stock. Furthermore, doing so could increase consistency in the commissioning process, improve the reliability of building systems, and make the process of assessing performance, which is a critical part of retrocommissioning, a truly continuous process.

How might this be done? First, identify processes that produce the desired outcomes that could be done automatically. Then develop building equipment, systems, control systems, and tools that implement these processes automatically. Create a manual process (or processes) that fills the gaps between the automated processes ensuring that the activities that absolutely require human intervention and tie the automated processes together are executed efficiently and cost effectively.

In the next two sections, we first provide a vision for commissioning in the distant future after the automated processes are fully developed and implemented using the evolution of automobiles over the last 10 or so years to their present state as an analogy. We then take a critical look at commissioning to identify the processes that require direct human involvement and processes that don't and could be automated. We then identify technologies that are key to realizing the automated processes and conclude by identifying research and development that will be essential to accomplishing our vision for commissioning of the future.

Before launching into the next section, we want to qualify our intent in this paper. We are not suggesting that commissioning and efforts to promote it be suddenly terminated today. On the contrary, we believe that commissioning as conducted today is important as a transition process. It provides important benefits, but as with most things, it needs improvement over time. Our vision is for the long term. It will not be realized tomorrow, but the vision can help guide R&D and product development decisions so they lead us to a future where the benefits of commissioning permeate the entire building enterprise. Likewise, as this technology and tools embodying it emerge, commissioning should adapt and change to assimilate these new capabilities, making the commissioning process faster, less expensive, more thorough, more consistent, more reliable, more cost effective, more continuous, and appealing to more of the market.

Commissioning for the Future—Highly Automated and Efficient

When operation of a new building or new piece of equipment or system is started in the future, with the push of a "start" button, equipment and systems should all test themselves, identify any installation or configuration problems, automatically fix problems amenable to "soft" solutions, and report the need for "hard" solutions requiring replacement or installation of hardware. A report on the performance of all building systems and equipment should be automatically generated, delivered to key recipients, and stored electronically for future reference and updating. During initial operation (e.g., for the first year), the system should optimize itself, integrating its behavior with external constraints, such as occupancy, occupant behavior and feedback, energy prices, demand charges, and weather. Although most of the optimization should take place during this initial period of say a year, the building systems should continue to optimize themselves as prices change, spaces are converted to different uses. tenants change, and building equipment itself ages and wears. Using prognostics, systems should automatically inform building staff regarding expected lives and recommended service times for equipment. Diagnostics should detect degradation and failure, make "soft" fixes when possible (alerting building staff to changes made and electronically documenting changes automatically made for future reference) and alert staff to impending failures and required maintenance to prevent them.

To a large degree, buildings in the distant future should operate themselves, even beyond what automobiles do today. The evolution of automobile technology might serve as a model (Capehart et al 2003) for the kinds of advancements possible and paths for realizing them. Achieving this level of automation for buildings may prove more challenging than for automobiles. Cars are mass produced in factories under controlled manufacturing conditions. Buildings in contrast are all unique, some more unique than others. Furthermore, they are mostly constructed on site, not in a factory. So, application of automation to building commissioning will present unique challenges, but methods under development (some examples of which are provided in the next section) are addressing these differences. Technology will evolve over time and change the practice of commissioning, bringing benefits to building owners and occupants. Ours is a vision for buildings of the future that automatically will perform many of the actions required to meet the objectives of commissioning, where technology will provide the cornerstone for achieving this future.

A Critical Look at Commissioning: Automation of Processes

The major tasks composing commissioning of new buildings and retrocommissioning of existing buildings are shown Table 1 by phase of the project. Some processes are critical to accomplishing the objectives of commissioning. Other processes exist to support commissioning specifically as it is performed today. If the overall process of commissioning were changed, some of these processes might become unnecessary or would be modified considerably. The same overall objectives might be achieved without an identical set of processes. Table 1 includes designations of whether activities would be manual (M) or automated (A) in a highly automated future for commissioning.

Commissioning objectives would be established largely by standards and specialized to specific projects by detailed objectives being automatically inherited by associating objectives with generic types of commissioning projects. For retrocommissioning, most activities would become a routine part of building operation and maintenance and would not require explicit development of objectives. Similarly, objectives associated with equipment startup would be unneeded because all equipment would be automatically started up and tested with standard automated start-up routines satisfying standard objectives.

Commissioning plans similarly would be specified automatically based on information automatically obtained from design documents and only limited information input manually (e.g., special constraints on schedules). Design information would be automatically stored as developed and shared throughout the life of the building. This would include objectives and intent behind the design. Automatic storage and universal data sharing protocols would eliminate the need to manually take off information from drawings or re-input information developed in earlier phases. Ultimately, even existing buildings that were designed before automated data storage was routinely used, will possess systems that will automatically detect all aspects of the buildings, systems and equipment installed, generate the equivalent design, and evaluate it.

Designs will be automatically evaluated with respect to meeting design intents as well as energy and other standards. For many years, researchers have studied the design process and developed methods for automating both design generation and evaluation. A sampling of issues and advancements in design automation can be found in Gero 2002, Gero 2000, Caldas and Norford

2002, Iliescu et al. 2000, Fleming and Waterbury 1995, and Fleming and Aygen 2001. Research in these fields will provide the basis for automation of design review and revision performed as part of commissioning. To the extent that commissioning specifications are still required in bid documents far in the future, most of the required language might be generated automatically, reviewed manually, and revised manually in special cases where required, but all documents will be reviewed automatically eventually. Computer-based tools will parse text and "interpret" the meaning, and evaluate it with respect to needs and design criteria. Given information about the equipment and systems in a building or specified by the design, checklists (to the extent still needed) could be generated automatically. With some exceptions, most checklists would be eliminated because checks would be performed automatically. Just-in-time facility documentation (Song et al. 2002) may become the basis for operation and even parts of commissioning and retro-commissioning. Even proper installation of equipment (e.g., whether any fans are installed backwards) could initially be checked automatically. Some problems might require visual inspection after initial automatic detection of problems, but the labor for this would be highly targeted to problem situations.

Table 1. Major Commissioning and Retrocommissioning Activities

New Construction Commissioning	Retrocommissioning Existing Buildings
1. Conceptual or pre-design phase a. Develop commissioning objectives (A) b. Hire commissioning provider (M) c. Develop design phase commissioning requirements (A) d. Choose the design team (M)	**1. Planning phase** a. Develop commissioning objectives (A) b. Hire commissioning provider (M) c. Review available documentation and obtain historical utility data (A) d. Develop retrocommissioning plan (A)
2. Design phase a. Commissioning review of design intent (A) b. Write commissioning specifications for bid documents (A) c. Award job to contractor (M)	**(No design phase activities)**
3. Construction/installation phase a. Gather and review documentation (A) b. Hold commissioning scoping meeting and finalize plan (M) c. Develop pre-test checklists (A) d. Start up equipment or perform pre-test checklists to ensure readiness for functional testing during acceptance (A)	**2. Investigation phase** a. Perform site assessment (M/A) b. Obtain or develop missing documentation (A) c. Develop and execute diagnostic monitoring and test plans (A) d. Develop and execute functional test plans (A) e. Analyze results (A) f. Develop Master List of deficiencies and improvements (A) g. Recommend most cost-effective improvements for implementation (A)
4. Acceptance phase a. Execute functional tests and diagnostics (A) b. Fix deficiencies (M) c. Retest and monitor as needed (A) d. Verify operator training (A) e. Review O&M manuals (A) f. Building/retrofit accepted by owner (M)	**3. Implementation phase** a. Implement repairs and improvements (M) b. Retest and remonitor for results (A) c. Fine-tune improvements if needed (A) d. Revise estimated energy savings calculations (A)
5. Post-acceptance phase a. Prepare and submit final report (M/A) b. Perform deferred tests (if needed) (A) c. Develop recommissioning plan/schedule (A)	**4. Project hand-off and integration phase** a. Prepare and submit final report (M/A) b. Perform deferred tests (if needed) (A) c. Develop recommissioning plan/schedule (A)

Source: Haasl and Sharp 1999

All testing, data collection, analysis, and interpretation of results would be performed automatically. Examples of how some tests could be executed automatically today are given by Katipamula et al. 2003a, Katipamula et al. 2003b, and Brambley and Katipamula 2003. These capabilities are based on research and development in the fields of automated fault detection, diagnostics and prognostics.[1] "Fixing deficiencies" and "implementing repairs and improvements" are designated in Table 1 as being done manually; however, only repairs and improvements requiring physical repair, replacement, of reinstallation require human intervention. As shown in Katipamula et al. 2003a and 2003b, some repairs such as revising control code, changing set points, and recalibrating sensors might be done automatically with no human intervention except to read a short report from the computerized system regarding actions it took. Automatically retuning of control algorithms is also possible today for some applications and most tuning will be done automatically in the long-term future.

As indicated in Table 1, most commissioning activities will be done automatically at some time in the future. People will still need to coordinate the processes and ensure that reporting to owners and management is appropriate, but many of the commissioning activities executed manually today will become automatic. This transformation will reduce the labor, time, and cost of commissioning and help overcome some of the key barriers that widespread application of commissioning faces today. Reaching that future, however, will require advances in key enabling technologies and then application of them to building systems. Table 2 provides a list of key technologies needed to achieve this future and the capabilities for commissioning that each might provide.

Wireless data communication will eliminate many of the wires required today to collect data or transmit control signals to device actuators. Wires can represent a significant fraction of the cost of a sensor or control point. As a result, wireless communication for sensors and controls will enable more ubiquitous use of sensing, increasing information on the operating state of systems and equipment available at any point in time and enabling better control and maintenance. Plug and play controls and equipment will enable quicker installation and set up of physical systems and controls. Controls will ultimately become self-writing, given some input on the performance objectives for the building. Small, embedded, networked processors will distribute control to a greater degree than today's control systems, leading to better, higher resolution, system response while coordinating through networking with other subsystems and components to achieve building-level objectives.

Automated fault detection and diagnostics will lead to greater awareness of system conditions throughout buildings on a continuous basis. Corrective actions will be enacted automatically by "aware" agents capable of correcting faults in some cases (e.g., correcting a control schedule or fixing an incorrect set point). In cases where automatic fault correction is not possible, notifications will be provided to building staff and management regarding faults and their costs. No longer will faults go unrecognized or will an engineer need to study data patterns to detect them. The operating state of building systems will be known along with the performance and cost impacts of problems so priorities for operation and maintenance can be made with complete information. Prognostic techniques will automatically predict the remaining serviceable life of equipment and suggest condition-based maintenance actions. Automated proactive testing will be the basis for short-term functional testing. These tests allow a wide range of conditions to be simulated over a relatively short period of time so that problems can be detected faster than if

[1] A comprehensive review of fault detection, diagnostic, and prognostic methods can be found in Katipamula and Brambley 2005, and a recent review of tools using such methods is provided by Friedman and Piette 2001.

only passive observation of routine operation is used. Proactive testing will enable consistent performance of functional tests automatically during initial commissioning and then at regular periods throughout the life of the building.

Table 2. Technologies Needed for Highly Automated Commissioning

Technology	Potential Applications
Wireless sensing, data acquisition, and control	Cost effective sensing and data collection Condition monitoring
Plug and play building equipment and controls	Rapid automatic self-configuration of controls Automatic control algorithm selection and application Self-identifying equipment and automatic system design recognition
Embedded networked sensing and processing	Highly distributed processing of information with local control capabilities coordinated to meet system and building level objectives
Automated fault detection, diagnostics, and prognostics	Automatic detection and diagnosis of operation, equipment, and control faults Automatic detection and diagnosis of designs and hardware installations Automatic generation of maintenance plans Condition-based maintenance
Automated proactive testing	Automated startup and functional tests, analysis of data, and interpretation of results
Automatic records management and data exchange protocols	Automatic generation of plans and reports Automatic storage of data Automated asset tracking Automatic project management assistance

Fault detection and diagnostic methods will have applications in design review in addition to use on physical components. Diagnosis of design is similar to diagnosis of a physical device. First a problem or fault is detected with the design. Evaluation of the design indicates that it does not satisfy some criterion (requirement) it is intended to satisfy. This is analogous to fault detection. Then the reason for the fault existing (its cause) is identified or isolated, which is analogous to fault diagnosis or isolation. The design then needs to be revised to correct the deficiency, which parallels fault correction. When this entire process is automated, it will provide continuous review and evaluation of designs as they evolve. This will likely be done by automated agents (processes whose purpose is to execute part of the design review and report the results), each of which is responsible for evaluation with respect to a small subdomain. Some of these agents will specifically handle evaluations from the perspectives of commissioning.

Data exchange protocols will provide the basis for sharing data among automated agents as well as commissioning professionals, operating staff, and facility management. Radio frequency identification tags will also play a role in tracking assets as well as enabling easy, automatic identification of each piece of equipment and component, enabling automatic checking for consistency with specifications as equipment arrives on the construction site and assessing its installation. Tags may also provide physical and performance characteristics from manufacturer tests, which then will become available to processes that evaluate the correctness of installation, develop control algorithms, evaluate functional test results, and monitor performance. Together these technologies will enable realization of highly automated commissioning and operation.

The Path Towards Future Vision

The impediments to realizing a future where building commissioning and retrocommissioning are largely automated are both technological and social. The technology, however, is essential for realization of the vision. With it, automated capabilities for executing all but the management, repair, and replacement activities could be delivered as parts of equipment packages and control systems. Advances in each of the technologies identified in Table 2 will be needed. Because the buildings industries are highly fragmented, public R&D organizations will need to provide leadership to produce this technology. Even then, a market demand will need to develop to drive the creation of new equipment and control systems with automated commissioning capabilities. The building commissioning industry will evolve, gaining market share over time as energy and electric power prices increase and more burden for management of the electric power grid is pushed to end users. Penetrating the market will require improved cost effectiveness for commissioning, as well as education of building owners and operators regarding the benefits of commissioning. Commissioning will need to change in ways that reduce cost while preserving or even enhancing the returns on it. The practice of commissioning will likely change gradually over time with the introduction of new tools that automate parts of the process. Market transformation programs at the federal, regional, state and local levels can help spread the application of commissioning for the public good. Research, development, deployment and market transformation programs will be needed to accelerate the introduction of automated capabilities and the spread of commissioning, improving the performance of the building stock and bringing energy and environmental benefits. Still, the willingness of the commissioning profession to accept and embrace these technologies will be critical to determining their rate of penetration. Resistance won't stop the introduction of the technologies, only delay their application, but earlier acceptance will help accelerate capture of the benefits associated with high-quality, widespread commissioning even if the mechanism of delivery changes.

Conclusions

Automation could change the nature of the commissioning process for both new and existing buildings. The services performed today as part of commissioning of existing buildings should become part of routine operation and maintenance with automated monitoring, testing, and diagnosis continually performed by the building systems and equipment themselves, taking much of the responsibility off humans just like it is done in a modern day automobile.

Still, repairs and replacement of hardware will continue to require human intervention. Deteriorating bearings in pumps, failed windings in fan motors, and leaking valves will need humans to repair or replace them. Automation can only prompt repair technicians to take action to make repairs. For the commissioning cycle to be complete, humans will still need to respond to information provided automatically on maintenance needs.

The services provided by commissioning during design and construction should become integral parts of those phases of the building life cycle. Assurance of their proper consideration during these phases of building projects may still require an advocate, like the commissioning agent today, but ideally these responsibilities will be taken over by other members of design and construction teams. In any case, the provider of these services is likely to focus on design and construction, rather than responsibilities over the entire building life cycle.

System start up, like commissioning responsibilities during operation, is likely to become increasingly automated. Equipment and systems should become self-configuring, self-testing, and self-verifying. Even proper installation is likely to be automatically verified. Once again, though, when equipment and system components are found to be installed incorrectly, human technicians will still need to take responsibility to repair the installation. Equipment though may become intolerant to problems it detects (fail safe), refusing to start up until all problems it detects with the installation are corrected.

Automation will likely change the role of commissioning over time and in 20 or 30 years, its objectives may be met completely differently than they are today. These changes will not occur overnight but rather over many years, but they should lead to more cost effective delivery of the outcomes promoted by commissioning to a much broader segment of the commercial buildings market. Change is inevitable and will bring benefits. As with use of automation in design, detractors will find problems with greater use of automation in commissioning; proponents will grasp increased automation as an opportunity (Chastain 2002). The authors recommend that the building commissioning community embrace the opportunities posed by new technology and employ them to deliver better services. As Barrow (2004) observes regarding the opportunity for architecture to benefit from information technology, we also believe for commissioning:

> "The savvy, who are dynamic in their thinking and technologically adaptive, will flourish with the establishment of a long range dynamic vision, understanding and engagement of emerging new project delivery methodologies, commitment to management or specialization, and adoption of congruent technology."

Research and development will be required to achieve the benefits of greater automation in commissioning but so will adoption by the various players in the commissioning and broader buildings communities. Researchers and providers of services have the opportunity by sharing a vision like the one presented in this paper to work in concert to more rapidly and more effectively capture the benefits targeted by commissioning.

References

Barrow, L. 2004. "Elitism, IT and the modern architecture opportunity or dilemma." *Automation in Construction* **13**(2):131-145.

Brambley, M. R. and S. Katipamula. 2003. "Automating Commissioning Activities: Update with Examples." In *Proceedings of the 11th National Conference on Building Commissioning*, May 20-22, 2003. Portland, Ore.: Portland Energy Conservation Inc.

Capehart, Barney L., Harry Indig, and Lynne C. Capehart. 2002. "If Buildings were Like Cars – the Potential for Information and Control Systems Technology in New Buildings." *Solutions of Energy Security and Facilities Management, WEEC Proceedings.* J. Wells (ed.). New York, N.Y.: Marcel Dekker.

Caldas, L. G. and L. K. Norford. 2002. "A design optimization tool based on a genetic algorithm." *Automation in Construction* **11**(2):173-184.

Chastain, T., Y. E. Kalay and C. Peri. 2002. "Square peg in a round hole or horseless carriage? Reflections on the use of computing in architecture." *Automation in Construction* **11**(2):237-248.

Claridge, David E, Charles H. Culp, Mengsheng Liu, S. Deng, Wayne D. Turner, and Jeffery S. Haberl. 2000. "Campus-Wide Continuous Commissioning^{SM} of University Buildings." In *Proceedings of the 2000 ACEEE Summer Study*. Washington, D.C.: American Council for an Energy Efficient Economy.

Fleming, U. and Z. Aygen. 2001. "A hybrid representation of architectural precedents." *Automation in Construction* **10**(6):687-699.

Fleming, U. and R. Waterbury. 1995. "Software Environment to Support Early Phases in Building Design (SEED): Overview." *Journal of Architectural Engineering* **1**(4):147-152.

Friedman, H. and M.A. Piette. 2001. *Comparitive Guide to Emerging Diagnostic Tools for Large Commercial HVAC Systems.* LBNL Report 48629. Berkeley, Ca.: Lawrence Berkeley National Laboratory.

Gero, J. S. 2000. "Developments in computer-aided design," in *INCITE 2000,* H. Li, Q. Shen, D. Scott and P. Love (eds.), pp. 16-24. Hung Hom, Kowloon, Hong Kong: HKPU Press.

Gero, J. S. 2002. "Advances in IT for building design," in *Advances in Building Technology,* M. Anson, J. Ko and E. Lam (eds.), pp. 47-54. Amsterdam: Elsevier.

Haasl, Tudi and Terry Sharp. 1999. *A Practical Guide for Commissioning Existing Buildings,* Portland, Ore.: Portland Energy Conservation Inc. and Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Iliescu, S., P. Fazio and K. Gowri. 2000. "Similarity Assessment in a Case-Based Reasoning Framework for Building Envelope Design," in *INCITE 2000,* H. Li, Q. Shen, D. Scott and P. Love (eds), pp. 697-713. Hung Hom, Kowloon, Hong Kong: HKPU Press.

Katipamula, S. and M. R. Brambley. 2005. "Methods for Fault Detection, Diagnostics and Prognostics for Building Systems – A Review." accepted for publication in 2005 by the *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research.*

Katipamula S., M. R. Brambley, and L Luskay. 2003a. "Automated Proactive Commissioning of Air-Handling Units." Report PNWD-3272. Richland, Wash.: Battelle Pacific Northwest Division. Also published by the Air-Conditioning & Refrigeration Technology Institute, Washington, D.C. Available online: www.arti-21cr.org/research/completed/finalreports/30040.pdf.

Katipamula, S., M. R. Brambley, and L. Luskay. 2003b. "Automated Proactive Techniques for Commissioning Air-Handling Units," *ASME Journal of Solar Energy Engineering*, *Transactions of the ASME*, Special Issue on Emerging Trends in Building Design, Diagnosis and Operation **125**(1):282-291.

Liu, Mengsheng, Claridge, David E, and Wayne D. Turner. 2002. "Continuous Commissioning[SM] Guide Book." Washington, D.C.: Federal Energy Management Program, U.S. Department of Energy. Available on the worldwide web at: http://www.eere.energy.gov/femp/pdfs/ccg01_covers.pdf.

Liu, Mengsheng, Claridge, David E, and Wayne D. Turner. 2003. "Continuous Commissioning[SM] of Building Energy Systems." *ASME Journal of Solar Energy Engineering*, *Transactions of the ASME*, Special Issue on Emerging Trends in Building Design, Diagnosis and Operation **125**(3): 275-281.

Portland Energy Conservation, Inc. (PECI). 1997. *Commissioning for Better Buildings in Oregon*. Salem, Ore.: Oregon Energy Office.

PECI. 2000. *New Construction Commissioning Handbook for Facility Managers*. Salem, Ore.: Oregon Energy Office.

Quantum Consulting. 2003. *Market Progress Evaluation Report--Commissioning In Public Buildings Project, No. 3*, Report #E03-107. Portland, Ore.: Northwest Energy Efficiency Alliance.

Song, Y., M. J. Clayton, and R. E. Johnson. 2002. "Anticipating reuse: documenting buildings for operations using web technology." *Automation in Construction* **11**(2):185-197.

U.S. Department of Energy (DOE) and U.S. General Services Administration (GSA). 1998. *Building Commissioning Guide, Version 2.2*. Washington, D.C.: U.S. Department of Energy, Federal Energy Management Program (FEMP) and U.S. General Services Administration, Public Buildings Service.

U.S. DOE. 2002. *National Best Practices Manual Commissioning*. Washington, D.C.: U.S. Department of Energy.

U.S. DOE. Undated. *Building Commissioning – The Key to Quality Assurance*. Washington, D.C.: U.S. Department of Energy, Rebuild America Program.