NISTIR 7356

State-of-the-Art Review for Commissioning Low Energy Buildings: Existing Cost/Benefit and Persistence Methodologies and Data, State of Development of Automated Tools and Assessment of Needs for Commissioning ZEB

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Prepared for:
The U.S. Department of Energy
Energy Efficiency and Renewable Energy
Office of Building Technology, State and Community Programs

August 2007

U.S. Department of Commerce
Carlos M. Gutierrez, *Secretary*

National Institute of Standards and Technology
William A. Jeffrey, *Director*

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This work was carried out as part of the U.S. contribution to the International Energy Agency/Energy Conservation in Buildings and Community System's research project: Annex 47 on Cost-effective Commissioning of Existing and Low Energy Buildings.

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Executive Summary

This report documents the findings of a review of the state of the art in the commissioning of low energy buildings.

The purpose of this report is threefold:

1) To identify and assess existing methodologies for defining the costs and benefits of commissioning, including the persistence of benefits;
2) To review and assess the state of the art in automated and semi-automated commissioning tools; and
3) To assess current practices for commissioning low energy buildings and identify the needs for methods and tools that go beyond what conventional commissioning approaches can offer.

Specific R&D recommendations are included in each chapter of the report and a summary is included in the Conclusions on page 89.

Chapter 1: Review of Commissioning Cost-Benefit Methodologies and Data

This chapter assesses the cost and benefit methodologies employed in 11 commissioning studies. Among these studies, there is no standard methodology for determining costs and benefits and the reported cost and benefit figures vary widely. Cost and benefit methodologies have been categorized as simple, moderate, or complex based on their level of complexity. One commonality exists across cost, energy and non-energy benefit methodologies: only complex methodologies validate the data.

It is apparent that the methodology significantly impacts reported costs and benefits. *Commissioning costs* trend upward as the cost methodology becomes more complex. This is likely because more cost categories are taken into account. *Non-energy benefits*, on the other hand, are reported as higher when a moderate methodology is employed. This is likely due to the difference between "avoided cost" calculations, used in moderate methodologies, and "willingness to pay" calculations, used in complex methodologies.

Three recommendations were derived from this assessment of existing cost-benefit methodologies:

- Building commissioning data should be greatly diversified. The pool of buildings from which data are drawn should be expanded, as most of the data in these studies come from a small pool of commissioning projects and providers.
- The data collection strategy must be matched to the data requirements of the cost and benefit methodologies. Complex methodologies, and even moderate methodologies, should aim to collect data using an ongoing, rather than retrospective, procedure. One way to do this is to facilitate the ability of respondents to enter their own data in real-time. An automated or semi-automated analysis tool could also be used to facilitate ongoing analysis.
- Data validation is an important aspect of any cost-benefit methodology. In cases where data are not verified, the accuracy of the cost-benefit results may be at risk.

Chapter 2: Review of Persistence of Commissioning Measures in New and Existing Buildings

This chapter provides an overview of persistence studies in both new and existing building commissioning projects. Interest in the persistence of the benefits of commissioning has been growing, but the topic is still relatively new. The only relevant projects identified in the literature to date involve a total of 37 buildings, of which ten are in Texas, 13 are in California, 13 in Oregon and one is in Colorado.

In retrocommissioned buildings, savings generally decreased with time, but there is wide variation from building to building. For the buildings where savings persistence was quantified, savings persistence at the time of the study (3 to 8 years after commissioning) ranged from about 50 % to 100 % in all but one or two buildings. Average savings at the time of the study were about ¾ of the original savings, with the most dramatic savings take-backs were caused by undetected mechanical or control component failures.

In the 10 new buildings studied, over half of the 56 commissioning fixes persisted. Hardware fixes, such as moving a sensor or adding a valve, and control algorithm changes that were reprogrammed generally persisted. Control strategies that could easily be changed, such as occupancy schedules, reset schedules, and chiller staging tended not to persist. Persistence was also related to operator training.

As is evident, the number of buildings studied here represents a very small portion of commercial buildings that have undergone commissioning or retrocommissioning. More research is needed to:

- Develop a uniform methodology for determining commissioning persistence.
- Determine the persistence of savings from a broader sample of buildings.
- Develop simple tools for tracking performance of commissioning measures.
- Develop practical methods for owners and operators to better maintain commissioning savings.

Chapter 3: Review of Automated Commissioning Tools for Buildings

This chapter reviews state of the art automated and semi-automated commissioning tools. Automated commissioning is viewed as a means to speed up the commissioning process and reduce dependence on scarce and relatively expensive skilled practitioners. A number of automated state of the art tools have been developed and tested at research institutions and universities with funding from utilities, industry, and government agencies.

The tools developed to date can broadly be categorized as tools to *evaluate the performance of systems* or tools that *automate other aspects of the commissioning process*. Three commissioning tools (ENFORMA, PACRAT, and Virtual Mechanic[1]) currently available on the market and six prototype tools are described in the report. These tools, which have been developed for a variety of conventional HVAC systems, address various aspects of initial commissioning and recommissioning/ongoing

[1] *Disclaimer: Certain trade names and industry standards are mentioned in the text to illustrate market-available products. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.*

commissioning. In addition, there are a number of enabling tools that are valuable resources to facilitate the implementation of the commissioning process and the development of new tools.

It is anticipated that the use of automated or semi-automated commissioning tools, combined with advances in diagnostics research, will enable more people to perform these functions in a more efficient manner. Overall, there is good but limited anecdotal evidence showing the value of these automated commissioning tools. However, the tools are few and are generally limited to selected HVAC systems. Available and emerging tools need to be more robust to increase potential applications. This growing area of research is expected to further broaden the market for commissioning.

Chapter 4: Review of Needs and Challenges in Commissioning Zero Energy Buildings

This chapter presents a literature review of commissioning and operational experience with existing buildings that were designed to have low energy consumption. Key findings from a number of case studies, including the National Renewable Energy Laboratory (NREL) High Performance Buildings, are:

- Designers/ and contractors are not sufficiently familiar with innovative low energy designs.
- There is a lack of commissioning procedures for low energy buildings, so only the conventional features get properly commissioned.
- Deficiencies in design, construction and commissioning result in operational problems; however, many of these problems were only detected by the R&D team studying the building.
- Controls are a particular source of problems, in part because mechanical designers leave the control system design to the controls contractor, who is typically less experienced with innovative systems than the design team.

R&D can help address these problems by:

- Developing methods of documenting design intent and performing design reviews that are adapted to the specific needs of innovative and low energy buildings.
- Developing functional test methods that adequately address innovative system operation and integration issues, capable of:
    A. Comparing expected energy performance to actual energy performance during commissioning and diagnosing causes of differences.
    B. Incorporating simulation as a means of enforcing accountability for energy performance between design and construction.

Chapter 5: New Functional Tests for use in Commissioning Zero and Low Energy Buildings

This chapter presents four new functional tests for systems with particular applicability/importance to low energy buildings:

- Radiant slabs for heating.
- Under floor air distribution plenum pressure.
- Demand-controlled ventilation.
- Building pressurization.

Conclusion
The overall conclusion of the report is that commissioning has a key role to play in comprehensive quality assurance for the design, construction and operation of buildings. Quality assurance tools and procedures are necessary to ensure that the technical potential of building systems and components is realized in operation throughout the life of the building.

Overview

Building Commissioning [2] is a quality assurance process for the design construction and operation of buildings. Although it is recognized as a valuable means to ensure that buildings reach their operating potential, the process is not widely adopted. The principle barrier to market penetration is the high cost, or the perception of high cost, of commissioning. Reducing the cost through automation is one approach to improving cost-effectiveness. Documenting the costs and the benefits, and disseminating that information is widely seen as critical to increasing the uptake of commissioning. The increased use of innovative, interacting, systems in low or zero energy buildings both increases the importance of commissioning these buildings and requires the development of commissioning methods and procedures for these systems.

This report documents the findings of a review of the state of the art in the commissioning of low energy buildings. The aims of this effort were to: 1) identify existing methodologies for defining the costs and benefits of commissioning, including the persistence of these benefits, and 2) to assess current practices for commissioning low energy buildings and identify the needs for methods and tools that go beyond what conventional commissioning approaches can offer.

The development of standardized methodologies for cost-benefit of commissioning, the evaluation of persistence of savings, and automated tools for commissioning are seen as a means to break down existing barriers. This literature review seeks to absorb the lessons learned in key studies and to distill the information into a format that can useful in the development of a plan for future work. The insight gained from this literature review and lessons learned from international applications will be used to develop a work plan for the International Energy Agency's Energy Conservation in Buildings and Community Systems' (IEA ECBCS) Annex 47 and will provide input to the Department of Energy's (DOE) effort to develop a multi-year plan for research and development to overcome the barriers to widespread use of commissioning in commercial buildings.

The report is organized as follows. The first chapter presents a review of cost-benefit methodologies and data. It presents the findings of 11 studies and discusses data collection strategies including the research-driven model, provider-driven model, and the database model. It presents methodologies for determining costs, energy benefits and non-energy benefits. Finally, recommendations are made for future work.

The second chapter addresses the persistence of commissioning measures in new and existing buildings. It presents detailed summaries of existing building and new building

[2] Commissioning- Clarifying Owner's Project Requirements (OPR) from viewpoints of environment, energy and facility usage, and auditing and verifying different judgments, actions and documentations in the Commissioning Process (CxP) in order to realize a performance of building system requested in the OPR through the life of the building

Initial Commissioning, Re-commissioning, Retro-commissioning, and On-going Commissioning are defined in the Glossary of Terms produced by ECBCS Annex 40.

studies. Strategies are discussed for improving persistence in new and existing buildings, including: design review, building documentation, operator training, building benchmarking, energy use tracking, trend-data analysis and re-commissioning.

The third chapter presents the state of the art in automated commissioning tools. It presents the three automated commissioning tools that are available commercially along with six prototypes that are at various stages of development. Chapter Three also presents related research, which includes the development of a number of tools that advance the automated tool development efforts. Finally, an overview of the state of market penetration is presented that highlights key barriers and assesses the potential for automated tools to facilitate aspects of the commissioning process.

The final chapter addresses the particular issues that pertain to the commissioning of very low energy buildings. A literature review of commissioning and operational experience with existing buildings that were designed to have low energy consumption has been undertaken. Key findings from a number of case studies are reported and generic conclusions with implications for R&D are presented.

Chapter 1: Review of Commissioning Cost-Benefit Methodologies and Data

I. Introduction

This chapter summarizes findings from a review of 11 commissioning cost-benefit studies. The chapter focuses specifically on the methodologies used to determine the costs and benefits of commissioning. In order to maintain this focus, only studies that make their methodologies explicit have been included. The majority of methodologies that were analyzed are research studies of multiple buildings, and only a few are case studies of just one or two buildings. A more exhaustive list of studies that include cost and benefit data, but not an extensive methodological discussion, can be found in the bibliography.

These 11 studies represent a variety of formats and intentions, which were each created to meet the funder's goal. Among them are research reports, databases of cost-benefit information and a glossy, marketing-style brochure. Most of the research reports were undertaken to produce data to support utility and research programs and to help owners and commissioning providers gather the financial justification needed to implement commissioning (Cx) or retrocommissioning (RCx).

There is a significant difference in methodological framework between studies implemented as "one-time" or "snapshot" analyses, and those set up to continually collect and incorporate new data. It is probably true that any methodology can be implemented on a continuous basis if its funding is also continuous. However, data collection methodologies that facilitate data entry by allowing respondents to easily enter their own data and use an automated or semi-automated analysis tool are better positioned for ongoing analysis.

Tables 1.1 and 1.2 provide a more detailed overview of the studies included in this chapter.

Table 1.2 describes the studies, including their format, expected use and audience, and any caveats and considerations that might affect how their conclusions are interpreted. Four of the studies were originally conducted as research projects, funded by government agencies and a non-profit corporation.[3] Nine reported their findings in published conference papers.[4] Of the two that were never published as conference papers, one is a glossy brochure produced for marketing purposes and the other is an article written for subscribers to an energy research and information service.[5]

[3] Funders were: U.S. Department of Energy, U.S. Environmental Protection Agency, Lawrence Berkeley National Laboratory, Northwest Energy Efficiency Alliance.
[4] Conferences were: American Council for an Energy Efficient Economy Summer Study, National Conference on Building Commissioning.
[5] Energy information service is ESource.

Table 1.2 provides a side-by-side comparison of the studies' data and findings. They represent a wide range of methodological approaches and resulting data on the costs and benefits of commissioning. Their data ranges from case studies of one to six buildings to more extensive analyses of 16 to 21 buildings to two meta-analyses of data collected and analyzed by others, one of 44 buildings and the other of 175 buildings. Among building projects studied there is wide range in building size and type and in findings. Cost, benefit and simple payback ranges are summarized in Table 1.1:

Table 1.1. Summary of Costs and Benefits from 11 Studies[i]

	New construction	Existing buildings
Commissioning costs	$\$2.05/m^2$ to $\$10.76/m^2$ ($\$0.19/ft^2$ to $\$1.00/ft^2$)	$\$0.86/m^2$ to $\$3.34/m^2$ ($\$0.08/ft^2$ to $\$0.31/ft^2$)
Energy benefits	$\$0.54/m^2$ to $\$6.89/m^2$ ($\$0.05/ft^2$ to $\$0.64/ft^2$)	$\$1.18/m^2$ to $\$2.80/m^2$ ($\$0.11/ft^2$ to $\$0.26/ft^2$)
Non-energy benefits	$\$1.40/m^2$ to $\$22.60/m^2$ ($\$0.13/ft^2$ to $\$2.10/ft^2$)	$\$1.18/m^2$ to $\$1.94/m^2$ ($\$0.11/ft^2$ to $\$0.18/ft^2$)
Simple payback	4.8 years to 6.5 years	0.7 years to 3.2 years

[i] Costs and benefits are presented as ranges to demonstrate the variances in the studies examined. Median or average values are not presented because underlying methodologies differ widely and such figures would not reflect actual costs and benefits experienced by building owners.

Table 1.2. Description of Cost-Benefit Studies (continued on next page)

Study/Author	Format	Use/Audience	Caveats and considerations
Stum, ECM Cx (1994)	Conference paper	Research	▪ Only energy conservation measure (ECM) commissioning is studied – not whole building commissioning. ▪ Utility program costs are included as a cost of commissioning. ▪ This early study does not address non-energy benefits (NEBs).
Piette, Energy Edge Cx (1995)	Technical report	This was one of the first studies to show savings concretely, and audience is program planners, technology developers.	▪ The study is focused on commissioning of ECMs in new construction, although additional unrelated deficiencies were reported. ▪ Some of the data collection and analysis were associated with a broader evaluation project.
Haasl, 5 Building Study (1996)	Conference Paper	Funded by the U.S. Environmental Protection Agency, Global Change Division, and the U.S. Department of Energy to help formulate energy conservation policy and programs.	▪ The study was an "Operations and Maintenance (O&M) investigative case study." ▪ No detail provided on the standard energy calculations or modeling scope. ▪ NEB analysis was still in progress. ▪ Stated objective was to "demonstrate that energy saving opportunities exist… and can be realized through improvements in O&M."
PECI/DOE, Deficiency Database (1996)	Research report	DOE-funded to document deficiencies found through Cx and RCx.	▪ While technically not a cost-benefit methodology itself, this method offers insight into the value of incorporating a detailed deficiency database into any cost-benefit methodology. ▪ Savings data only available for 35 deficiencies. ▪ A deficiency database may be a lower cost version of a cost-benefit methodology. Typically Cx reports have some detail on measures at a findings level through an issues log or punchlists. Cx reports do not always have comparable detail regarding quantification of energy savings or non-energy savings and a cost accounting procedure. A deficiency database leads to an understanding of where the most common problems lie.
Gregerson, RCx (1997)	Report for members of ESource	Audience was ESource members (utilities, ESCOs, Cx providers, researchers), to quantify a new field of efficiency opportunity	▪ Few reports cited measure costs and savings. Savings may be estimated, or as with the Texas LoanSTAR program (75 % of square footage in the study sample) per-building costs were estimated. ▪ The first major summary report on RCx.
PECI, Brochure (1997)	Glossy brochure	Audience was owners and Cx providers, for marketing.	▪ Summary metrics by sector, Cx and RCx mixed. ▪ Original data not available.
Altweis (2001)	Conference paper documenting methodology and detailed assumptions	Paper's audience was Cx providers, to encourage them to collect and report such data. Audience for data is owners and prospective customers.	▪ Very small sample size, suitable for case studies or research projects. ▪ A wide range in savings reported, due to highly varying assumptions (scenarios). ▪ Savings calculation methodology will vary from Cx Agent to Cx Agent, no standard calculation provided (although the methodology is conceptually well defined). ▪ No discussion of costs.

Study/Author	Format	Use/Audience	Caveats and considerations
Mills, **Meta-analysis** (2004)	Excel database, Research report	Statistical analysis for US Dept. of Energy	▪ Largest Cx cost-benefit study to date. Focused on obtaining large number of projects to get a high-level view of Cx metrics. ▪ Relied on availability, quality, and comparability of different primary data sources. ▪ Majority of building information comes from a few sources, especially for RCx. ▪ Merits of Cx should be assessed based on the cost-effectiveness of the proposed measures, not necessarily only on what was implemented. ▪ May inappropriately attribute or not attribute costs to the Cx process since cost accounting conventions are not always followed. ▪ May underestimate benefits because energy savings from all measures are not captured in Cx reports, NEBs are not usually expressed in monetary terms, and financial benefits in terms of increased net operating income (NOI) are rarely determined. Furthermore, in a few projects studied, measured savings exceeded predicted savings. ▪ Time consuming to gather project information from secondary sources and interpret it, as opposed to having the cost-benefit data entered by the people involved with the project.
SBW, Northwest Cx & RCx (2004)	Research report	Utility program evaluation	▪ Cost calculations include many costs associated with Cx, so figures may be higher than other studies. ▪ Non-energy benefits calculations based on opinion of team members (willingness to pay and/or perceived value).
California Commissioning Collaborative's Cxdatabase.com (2004)	SQL database, exportable to Excel One-page "datasheet" on each project Conference paper describing database	Researchers – data that supports Cx research and utility incentive programs Owners – defining the value of Cx to their business through data and case studies Providers – third party source from which to give owners information. Help raise the bar for Cx documentation of results	▪ Data is stored as-entered by respondents – no analysis performed unless brought in by outside researchers ▪ Datasheet is a one-page summary form automatically populated by data entered by respondents. ▪ Little population of the database as of February, 2006. ▪ Database in beta development level. ▪ While the original vision for this data included creation of case studies, none have yet been created.

II. Data Collection Strategies

By far the most common data collection method is the Researcher-Driven Model, in which a researcher was tasked with collecting and analyzing data. In more than 90 % of the studies a researcher was wholly or partially responsible for collecting documentation and data produced by others. In the handful that differed from this model, data collection was usually done "in house," because the researcher also served as the commissioning provider on the projects that were studied. In two cases, however, data collection was accomplished through use of a database allowing providers and owners to submit data independent of the researcher. A comparison of the data collection methodologies used in the different studies reviewed here is presented in Table 1.3.

The Researcher-Driven Model

In nine of the eleven studies, the data collection strategy was driven by a researcher who collected commissioning project information and produced a cost-benefit report. In eight of those nine, the researchers relied heavily on project documentation, primarily the commissioning provider's *Final Report*. Other documentation consulted included construction documents (for new buildings), issue logs and change orders. In more than half of the studies, other types of information were used to supplement written documentation. They include telephone surveys with key team members (two studies) and onsite inspection and monitoring (three studies).

When telephone surveys or interviews were employed, they were often used to gather data on non-energy benefits (NEBs). This is logical, given that NEBs are hardest to measure using commissioning or building documentation because they depend most on the experiences of the people who manage and occupy the building. In fact, there are two studies in which researchers were only interested in NEBs and in which the only source of data were telephone surveys and detailed interviews – no project documentation was collected (Haasl 1996; Bicknell 2004).

Among the nine studies that employed the researcher-driven model, there is much variation in the amount of data studied and level of detail collected, the logistics of obtaining documentation, and in supplemental types of data and the strategies for collecting it.

- **Quantity of data** varies from case studies of a single project to mid-range studies of five, six, 21 and 44 projects to two large studies of 175 projects each.
- **Level of detail** ranges from whole-project level metrics to metrics for individual issues.
- **Logistics of obtaining documentation** includes submission by a utility that collected all the documentation and turned it over to the researcher, submission by owners and providers directly to the researcher, and the gathering of documentation by the researchers from commissioning providers and other researchers.
- **Supplemental data** includes telephone surveys and onsite inspections.

In the researcher-driven model, data collection almost always takes place after the commissioning projects are complete and documentation finished. As a result, the effort required and the data quality depends almost entirely on the diligence of the parties responsible for producing the documentation (usually the commissioning provider, general contractor or testing and balancing agent). Time is also an issue. The closer the study is to project close-out, the more likely it is that project documentation will be available and in good condition, and that the important parties will be able to answer any questions.

The Provider-Driven Model

In two studies, the researcher and commissioning provider were one and the same. As a result, their studies were able to utilize very detailed data collected throughout the commissioning project. However, only a few projects were included, leading to these studies' designation as case studies rather than statistically significant research studies (Haasl 1996; Altweis 2001).

The Database Model

In two studies, researchers created interactive databases to collect commissioning project data. In one, the database was created through a collaborative effort in which multiple researchers and commissioning providers helped define required and minimum inputs (Cxdatabase.com). The database itself was created as an online application, meaning it was accessible on the Internet. Thus once it was released, commissioning providers could use it to enter information about their projects in real-time. In the other, a database of categories deficiencies was developed (PECI/DOE 1996).

A significant advantage to the database model of data collection is the ability of the researcher's needs to influence the commissioning provider's data retention efforts. Because providers know up-front what data the researcher wants, it can be supplied immediately while the documents are still available and the project is fresh in the provider's mind. On the negative side, a database alone is incapable of performing analysis, and this model requires funding for several things: design and programming of the database, a researcher to analyze the data or work with programmers to build analysis functionality into the database, marketing of the database to the provider audience, ongoing database maintenance and support, and perhaps even funding to compensate providers for entering data.

Explanation of Estimated Effort

Table 1.4 includes a column for "Estimated effort need to obtain and enter data." The amount of time and difficulty required to both collect and submit project data is estimated as either **low**, **moderate** or **high**. These rankings are not independently defined. Rather, they reflect the authors' estimate of the relative effort required to gather data according to the study's methodology, as compared to the other studies in this report. Thus a study with a "high" effort ranking was judged to employ a more time- and effort-intensive collection methodology than those deemed "low" or "moderate."

Table 1.3. Cost and Benefit Data (continued on next 2 pages)[i]

Study/ Year	# of buildings	Total and median bldg. size	Costs		Energy benefits		Non-energy benefits (NEBs)		Cost effectiveness	
			Cx	**RCx**	**Cx**	**RCx**	**Cx**	**RCx**	**Cx**	**RCx**
Stum, **ECM Cx** (1994)	6	218 722 ft^2 20 320 m^2		$3 060 overall $0.041/ ECM $0.08/$ft^2$ $0.86/$m^2$ **Simple**		37 412 kWh/y 5.3 % of orig. ECM Unrealized: 7.9 % **Moderate**		N/A		Recovered savings: $0.033/kWh Recovered + unrealized savings: $0.02/kWh
Piette, **Energy Edge Cx** (1995)	16	849 800 ft^2 78949 m^2 27 000 ft^2 (median) 2 508 m^2 (median)	$0.19/$ft^2$ $2.05/$m^2$ **Simple**	N/A	9.48 kWh/ft^2·y 102.04 kWh/m^2 $0.64/$ft^2$·y $6.89/$m^2$y **Complex**	N/A	not quantified	N/A	Simple payback: average 13.7 y; median: 6.5 y	N/A
Haasl, **5 Building Study** (1996)	5	837 000 ft^2 77 760 m^2 122 000 ft^2 (median) 1 313 197 m^2 (median)	N/A	$0.11/$ft^2$ $1.18 m^2 **Simple**	N/A	$0.11/$ft^2$ $1.18 m^2 **Simple**	N/A	Not quantified	N/A	Simple payback: 0.83 y (10 months)

Study/ Year	# of buildings	Total and median bldg. size	Costs		Energy benefits		Non-energy benefits (NEBs)		Cost effectiveness	
			Cx	RCx	Cx	RCx	Cx	RCx	Cx	RCx
PECI/DOE, Deficiency Database (1996)	16 Cx 28 RCx (44 total)	3 960 000 ft^2 367 896 m^2 67 000 ft^2 6 224 m^2 median	N/A	N/A	83 % of all deficiencies related to energy	92 % of operational deficiencies impact energy. Avg savings/ deficiency = \$892/y **Moderate**	51 % of all deficiencies related to reliability and maintenance	25 % of deficiencies related to comfort	N/A	N/A
Gregerson, RCx (1997)	44	8.84 million	N/A	Approx \$20 000 \$0.19/ft^2 \$2.05/m^2 **Simple**	N/A	Avg \$98 000 Median: \$41 000 19.2 % avg savings \$0.49/ft^2 \$5.27/m^2 **Moderate**	N/A	Not assessed	N/A	Simple payback: 0.9 y[6]
PECI, Brochure (1997)	75 Cx and RCx not separated	Not available	Median: \$0.15/ft^2 \$1.61/m^2		Not standardized metric **Moderate**		Improved (% of buildings): Thermal comfort: 42 % System function: 44 % Indoor air quality: 23 % O&M: 42 % **Simple**		Not assessed	
Altweis (2001)	1	14 350 ft^2 1 333 m^2	not reported	N/A	up to \$0.13/$ft^2 \cdot y$ \$1.40/m^2	N/A	\$0.17 - \$2.10/$ft^2 \cdot y$ \$1.83 - \$22.60/$m^2 y$ **Moderate**	N/A	not reported	N/A
Heinemeier, Schools Cx (2004)	1	N/A: methodology but no results.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[i] Dollar amounts have not been normalized to a common year. Methodological complexity listed in **bold**.

[6] Energy intensive buildings and even most of the efficient buildings had paybacks of less than two years.

Study/ Year	# of buildings	Total and median bldg. size	Costs		Energy benefits		Non-energy benefits (NEBs)		Cost effectiveness	
			Cx	RCx	Cx	RCx	Cx	RCx	Cx	RCx
Mills, **Meta-analysis** (2004)	175 projects RCx: 106 Cx: 69	30 400 000 ft^2 2 824 252 m^2 total 69 500 ft^2 6 457 m^2 (median Cx) 151 000 ft^2 14 028 m^2 (median RCx)	$74 267 $1.00/$ft^2$ $10.76/$m^2$ [0.6 % constr cost] **Moderate**	$33 696 $0.27/$ft^2$ $2.90 m^2 **Moderate**	$2533/y $0.05/$ft^2$·y $0.54/$m^2$·y **Moderate**	$44 629/y $0.26/$ft^2$·y 2.80m^2$·y **Moderate**	$51 000/y $1.24/$ft^2$·y 13.35m^2$·y **Moderate**	$17 000/y $0.18/$ft^2$·y $1.94 m^2·y **Moderate**	Simple payback: 4.8 y[7]	Simple payback: 0.7 y[8]
SBW, Northwest Cx & RCx (2004)	21	2.2 million ft^2 204 386 m^2	$71 791[9] $0.85/$ft^2$ $9.15/$m^2$ **Complex**	$22 053 $0.31/$ft^2$ $3.34/$m^2$ **Complex**	$9 856/y $0.09/$ft^2$·y $.97/$m^2$·y **Complex**	$13 678/ year $0.14/$ft^2$·y 1.51m^2$·y **Complex**	$13 609 (one-time) $0.13/$ft^2$ $1.40/$m^2$· **Complex**	$10 534 (one-time) $0.11/$ft^2$ $1.18/$m^2$ **Complex**	Direct pay-back: 7.5 y Total simple payback: 6.1 y	Direct pay-back: 4.0 y Total simple payback: 3.2 y
California Commissioning Collaborative's Cxdatabase.com (2004)	Two surveys completed, five in progress. Not assessed at this time due to lack of data and funding.									

[7] Standard energy prices corrected for inflation. Data normalized to $2003.
[8] Standard energy prices corrected for inflation Data normalized to $2003.
[9] Costs for this study include only Cx provider fees – although payback information includes additional costs, for example, costs to other parties.

Table 1.4. Comparison of data collection methodology (continued on next page)

Study/Author	Level of detail	Data sources (paid?)	Collection process	Timing of data collection	Data storage	Estimated effort needed to obtain and enter data
Stum, ECM Cx (1994)	Only looked at ECMs meriting greater resources (i.e. variable frequency drives, economizers)	Inspection reports, onsite inspection of ECMs in small comm. and retail	Reports provided by utility, onsite work done by authors.	Concurrent with and immediately following Cx activities	N/A	**Moderate** Onsite inspections but only of a few measures
Piette, Energy Edge Cx (1995)	Very detailed data collection on building characteristics to develop models,	Commissioning report, on-site data collection.	Extensive evaluation project.	Within one or two years after construction.	Unix-based database.	**High** Data for simulation.
Haasl, 5 Building Study (1996)	Data required for standard calculations and simulations.	Provider collected.	Data collected through RCx process, including two weeks of monitored data on key systems.	Collected during RCx process.	Not described.	**Moderate** Building and system characteristic data needed for modeling and calculation, and monitored data.
PECI/DOE, Deficiency Database (1996)	Findings level detail.	Half of data directly entered by Cx provider. Half by researcher (paid).	Review of final commissioning reports and issues logs.	Retrospective.	Database (Excel)	**Variable** Depends on availability and organization of necessary info in Cx documentation.
Gregerson, RCx (1997)	No detail other than metrics on a project-level. No measure-level detail.	Four Cx providers. 70 % from TAMU and 25 % from PECI	Building characteristics, EUI, and cost and energy savings figures requested from Cx provider by researcher.	Retrospective from final Cx reports.	Not specified.	**Low** Very minimal data collected (although retroactive so it may be difficult to obtain.)
PECI, Brochure (1997)	High level metrics	Cx provider	Phone interviews	Retrospective	Not specified	**Low** Minimal data collected (although retroactive so it may be difficult to obtain)

Study/Author	Level of detail	Data sources	Collection process	Timing of data collection	Data storage	Estimated effort needed to obtain and enter data
Altweis (2001)	Case study level data. Extensive detailed information required from project. Not difficult for the commissioning agent to obtain.	Commissioning agent collected information and conducted benefits analysis.	Commissioning provider review of notes and project documents.	Throughout the project.	Not specified.	**Low**, for commissioning provider. **High** for anyone else.
Heinemeier, Schools Cx (2004)	Report showed a great deal of detail, but the intent is to define metrics that are easily gathered, from review of construction documents.	Complete construction documents.	Researcher obtained a copy of and reviewed all construction documents.	After the project was complete.	Not specified.	**Moderate** Somewhat time-consuming to review all documents**.**
Mills, **Meta-analysis** (2004)	Based on the documentation available. Where little available, at minimum, project-level info was entered.	A few Cx providers and researchers entered many projects (paid). Smaller number of projects from unpaid Cx providers.	Review of past studies and final Cx reports/issues logs.	Projects completed between 1993 and 2004 Retrospective from final Cx reports and previous studies.	Excel spreadsheet	**Variable** Depends on availability and organization of necessary info in Cx documentation.
SBW, Northwest Cx & RCx (2004)	Identified all issues/findings, selected only significant and resolved issues	Extensive project documentation and surveys (both unpaid).	Project materials submitted by owner and telephone surveys with team.	While projects underway and within **1** year after close-out (early 2003)	Database (no specific software identified)	**High**
California Commissioning Collaborative's Cxdatabase.com (2004)	Three findings required, can accommodate unlimited number	Cx provider or owner. (unpaid, but funding for entering data desired, requirement was written into scope of some projects)	Respondent gathers data and enters into online forms.	Intended to be completed during project or immediately after completion. Can be completed at any time, if data is available.	Custom-built online database – project took several months at a cost of approx. $20,000. (www.Cxdatabase.org)	**Variable** Depends on whether respondent was aware of data requirements during the project and the quality of documentation.

III. Methodologies for Determining Costs, Energy Benefits and Non-Energy Benefits

Commissioning Costs

There is no widely used methodology for determining commissioning costs. To assist in the evaluation process, this report distinguishes three levels of complexity in cost methodologies: simple, moderate and complex.

Table 1.5 summarizes their differences in terms of which costs are included and if the costs are validated.

Table 1.5. Comparison of cost methodologies

	Cx Provider's fee	Resolution costs (RCx)	Costs to other parties	Validation method
Simple	X	X		
Moderate	X	X	X	
Complex	X	X	X	X

Of the 11 studies examined, all include the commissioning provider's fee as a cost of commissioning. Some include additional costs, for example, costs to other parties, although each study defines these costs differently. Only one study, with a complex methodology, makes an attempt to validate cost data by checking the respondent's data for consistency and to make sure cost figures fell within what researchers defined as a "reasonable range." (SBW Consulting 2004)

In general, the average cost of commissioning per square foot *increases* as the study's cost methodology *increases in complexity*. As Table 1.6 shows, in existing buildings the cost of commissioning steps upward as the methodology becomes more complex. In the case of new buildings, the cost of commissioning trends higher, with complex methodologies returning an average cost per square foot (square meter) slightly lower than moderate methodologies. Although not conclusive, it seems likely that the reported cost increases because complex methodologies account for costs incurred by several parties, whereas simple methodologies usually only account for the commissioning provider's fee.

Table 1.6. Average Cost of Commissioning by Methodological Complexity

	New Buildings		Existing Buildings	
Methodology	# of bldgs	Average Cost	# of bldgs	Average cost
Complex	13	$0.85/ft^2$ $9.15/m^2$	8	$0.31ft^2$ $3.34m^2$
Moderate	69	$1.00/ft^2$ $10.76/m^2$	106	$0.27ft^2$ $2.91m^2$
Simple	16	$0.19/ft^2$ $2.05/m^2$	50	$0.18ft^2$ $1.90m^2$

Below is a more detailed discussion of cost methodology types, with examples.

Simple. A simple methodology uses only one or two cost categories to arrive at the overall cost of commissioning. Usually these cost figures are relatively easy to obtain. Examples include the commissioning provider's fee and the cost to resolve an issue. In simple methodologies, these cost figures are self-reported and the study makes little or no attempt to validate the data.

An example of a simple methodology can be found in two early studies: Piette (1995) and Stum (1994). Piette calculated the cost of commissioning by taking a percentage of the overall energy efficiency measure cost. Stum defined the cost of commissioning as the self-reported commissioning provider's plus the administrative costs of the utility commissioning program that funded the projects.

Moderate. A moderately complex methodology uses more than two cost categories to arrive at the overall cost of commissioning. For example, cost categories could include incremental costs to all parties, travel costs, and negative impacts like increased change orders. Moderately complex methodologies include a broader array of costs in the cost of commissioning than a simple methodology, although the study stops short of applying a validation process to the data. The methodology may include differences in cost accounting between Cx and RCx.

An example of a moderate methodology can be found in Mills et al. (2004) and in Cxdatabase.com (2004). Mills et al.'s cost definition includes several figures: the provider fee, the coordination costs incurred by other parties and on RCx projects, the resolution costs. Cxdatabase.com's cost definition includes the provider fee, incremental costs incurred by other parties, the cost of O&M staff participation (if specified by the owner) and on RCx projects, the resolution costs. Neither Mills et al. nor Cxdatabase.com makes any attempt to verify the cost figures reported in project documentation or by respondents.

Complex. Like a moderate methodology, a complex methodology differentiates several categories of commissioning costs. However, studies employing complex methodologies do attempt to validate cost figures.

An example of a complex methodology is found in SBW Consulting (2004). Cost includes the provider fee, incremental fee increases for other parties, travel expenses and resolution costs. Researchers used a telephone survey to ask key commissioning team members 1) if they increased their bid for the project to account for commissioning activities and 2) if there were any significant non-labor costs associated with commissioning. Respondents were then asked to attach a dollar amount to each. If the respondent was unable to provide a dollar figure, researchers asked them to estimate the additional labor hours and provide a labor rate, from which researchers calculated the incremental cost to that respondent. As a quality assurance measure, researchers also evaluated whether the data supplied by respondents "were consistent and fell within reasonable ranges" (SBW Consulting 2004).

Energy Savings

There are a variety of methods for determining energy savings from commissioning. This study evaluates energy benefit methodologies, like cost methodologies, according to their level of complexity.

Table 1.7. Comparison of energy savings methodologies

	Issues ID and/or baseline comparison[10]	Energy calculations	Energy modeling	Normalization of energy data	Attention to measure interactions	Validation method
Simple	**X**					
Moderate	**X**	/	/	/		/
Complex	**X**	**X**	**X**	**X**	**X**	**X**

Key: X = always present; / = sometimes, but not always present

Of the 11 studies examined, all used either an issues identification or baseline comparison method to determine energy savings. Moderate methodologies employed some form of energy calculations, modeling, or data normalization. Only complex methodologies were attentive to measure interactions and data validation.

Below is a more detailed discussion of cost methodology types, with examples.

Simple. In existing buildings, simple methodologies compare before and after energy consumption without normalization of data. They may also obtain information directly

[10] Two methods for determining energy (and non-energy) savings are *issue identification* and *baseline comparison***.** In *issue identification* energy savings are determined first at the issue level and then added to arrive at the total savings for the project. The *baseline comparison* method looks only at whole-building energy benefits. The researcher establishes the building's "baseline" energy use and then compares it to energy use after commissioning. This method can be a more straightforward process in existing building projects, where there is a "before" snapshot. In new construction it is more difficult because the "baseline" is hypothetical and must be simulated.

from the building owner or manager regarding energy savings or comparisons of performance.

Examples of simple energy benefit methodologies are found in Cxdatabase.com (2004) and Heinemeier (2004). Cxdatabase.com asked survey respondents to provide energy savings numbers for each reported finding. Respondents were asked to also provide the calculations they used to arrive at the figures, but this information was not required. No standardized process for calculating energy savings was created. In Heinemeier's methodology, energy use per square foot of commissioned buildings was compared to those that were not commissioned. Building pairs were of similar size and type, and monthly utility bills were used to gather energy use data. Commissioned building energy use was also compared against standardized benchmarks.

Moderate. Moderately complex methodologies use project documentation to identify significant commissioning findings/issues that have been resolved, and then use engineering calculations or parametric modeling to determine the energy benefit. A validation process using measured data may be, but is not necessarily, applied. Moderately complex methodologies may also apply normalization techniques to before and after energy consumption.

An example of a moderately complex energy benefit methodology is found in the SBW Consulting (2004). Researchers used a three-step process, shown in Figure 1.1, to identify issues that resulted in a "stream" of energy and/or non-energy benefits. First they used

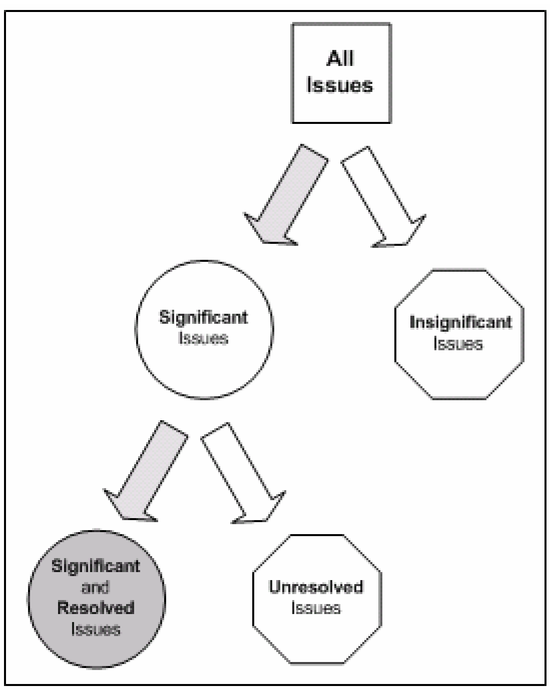

Figure 1.1. Sample issue identification methodology (SBW Consulting, 2004)

project documentation to identify all issues. Then they determined which issues were "significant" relative to their affect on total building area or occupants, resolution cost and/or long term impact. (SBW Consulting 2004) Of significant issues, they determined through documentation and/or telephone surveys which issues had been or would likely be resolved. Energy and non-energy benefits were only calculated for issues deemed significant and resolved.

Complex. Studies utilizing complex methodologies employ detailed engineering calculations or models to estimate energy savings. Examples range from detailed building simulations that require extensive information about building characteristics to very detailed engineering calculations based on measured data. Complex methodologies for new construction commissioning benefits address nuances such as the range of assumptions that go into the hypothetical baseline (i.e. what is assumed to have occurred without commissioning). More complex methods also address the interaction between commissioning measures, and the interaction with related activities like energy retrofits. Results can be reported per measure, or for a whole building (which is not simply the sum of individual measures).

An example of a complex energy benefit methodology is found in Altweis (2001). This study used engineering calculations to estimate energy use both with and without identified findings/issues. Researchers developed both a "most likely" and a "least cost solution" scenario, depending on assumptions about what would have occurred in the absence of commissioning.

Non-Energy Benefits (NEBS)

In the assessment of non-energy benefits there is a great diversity of methodologies in use. Here again, in Table 1.8, non-energy benefit methodologies are classified according to their complexity.

Table 1.8. Comparison of non-energy benefit methodologies

	Monetary value NOT assigned	Monetary value assigned	Monetary value validated
Simple	X		
Moderate		X	
Complex		X	X

Of the 11 studies examined, about half (five) do not assign a monetary value to NEBs. Those that do use methodologies ranging from simple processes that do not employ standard calculations or checks on respondents' information to a highly complex system in which NEB dollar values are calculated several different ways and the most conservative number selected. Here too, only the most complex methodologies attempt to validate the data.

Contrary to the direct relationship between methodological complexity and commissioning costs, with NEBs there appears to be an inverse relationship: the more complex the methodology the *lower* the monetary benefit reported. This holds true for both new and existing building commissioning.

It is apparent that methodology significantly impacts reported non-energy benefits. The study employing avoided cost calculations (a moderate methodology) returned higher savings than the study that determined the owner's perceived value of the benefit (a complex methodology). This is due to a fundamental difference between these two methodologies. Although both methods are hypothetical, avoided cost calculations estimate the full cost that *would have been incurred*, had the benefit not been received. Whereas the owner's perceived value is the amount the owner is *willing to pay* for the benefit – often less than the avoided cost. Further study in this area is clearly needed to determine how the non-energy benefit valuation method relates to the goals of the cost-benefit methodology.

Table 1.9 Non-Energy Benefits of Commissioning by Methodological Complexity [i]

	New Buildings		Existing Buildings	
Methodology	# of buildings	Average NEB Savings	# of buildings	Average NEB Savings
Complex	13	$0.13/ft^2$ $1.40/m^2$	8	$0.11/ft^2$ $1.18/m^2$
Moderate	23	$0.17/ft^2$ to $6.96/ft^2$ $1.83/m^2$ to $74.92/m^2$	10	$0.10/ft^2$ to $0.45/ft^2$ $1.08/m^2$ to $4.84/m^2$
Simple	no data		no data	

[i] Moderate data is presented as a range because a validation method was not employed.

Below is a more detailed discussion of non-energy benefit methodology types, with examples.

Simple. An example of a simple methodology for assessing non-energy benefits is found in Cxdatabase.com (2004). Here, respondents are asked to identify which benefits they received and have the option, but not the requirement, to supply a dollar value for the benefit. No standardized calculations are employed, and there is no process for evaluating the dollar values supplied by respondents.

Moderate. An example of a moderately complex methodology for calculating NEBs is found in Mills et al. (2004). Here, the researcher arrived at the NEB dollar value by adding the first-cost dollar value of non-energy savings and the ongoing labor cost savings, estimated as labor hours saved. Other NEBs were accounted for using a Yes/No checklist with an estimated dollar value supplied optionally.

Complex. An example of a complex methodology for assessing NEBs is found in SBW Consulting (2004), see Figure 1.2. Researchers developed three different ways to assign a dollar value to a "stream" of benefits flowing from a specific finding/issue, and then used the most conservative (lowest dollar value) estimate. All three calculations were based on the responses of key commissioning team members given in telephone surveys. (See Table 1.9 for additional details).

1. Willingness to pay (WTP)
Survey question:

"If all the non-energy benefits (and negative effects) that we talked about were taken away, what do you think would be the maximum amount you would be willing to pay to get back those benefits, on an annual or monthly basis?"

2. Sum of individual computed benefits
Respondents asked to compare the commissioning provider's fee to the specific commissioning benefit. All benefits are then summed for a total NEB value. An example survey question:

"Would you say that compared to your annualized commissioning costs, the contractor call-backs are…about 10 % more valuable, about 1 to 1.5 times more valuable, twice as valuable, more than twice as valuable?" Or, "Don't know/refused."

3. Overall net value
Respondents were asked to identify significant impacts from a given list (e.g., reducing operational deficiencies). Their responses were weighted, to give the opinions of providers and facility staff more importance than contractors and designers. The gross dollar value of each impact was then multiplied by the importance factor.

Figure 1.2. Sample complex NEB methodology (SBW Consulting, 2004)

Table 1.10. Overview of cost-benefit evaluation methodologies (continued on next 3 pages)

Study/Author	Costs		Energy Benefits		Non-energy Benefits (NEBs)		Persistence Assumptions	
Stum, ECM Cx (1994)	Simple	Cost of Cx provider services + program administration costs	Moderate	Engineering calculations and computer simulations from original ECM savings predictions	N/A		N/A	
Piette, Energy Edge Cx (1995)	Simple	Percent of overall energy efficiency measure cost, costs by energy-efficiency measure are used when available.	Complex	Used deficiency identification and post-construction utility data to tune as-built simulation models. Deficiencies were "removed" from the models to determine savings. Deficiencies categorized as Directly, Indirectly, and Un-related to the ECM, and Static or Dynamic.	Simple	Categorized as control, IEA, equipment life, O&M. No value assigned.	Simple (but the modeling itself was not simple)	"Low" and "High" lifetime scenarios defined in the modeling.
Haasl, 5 Building Study (1996)	N/A	N/A	Simple	Categorize deficiencies into deficiency type (maintenance, documentation, training, operations, installation, design); HVAC subsystem; and affected component. Additional categorization for controls related findings.	Simple	All deficiencies were categorized, including non-energy related deficiencies. In total (Cx and RCx), 51 % of all deficiencies related to reliability and maintenance (25 % significantly related). In total (Cx and RCx), 25 % of all deficiencies related to comfort (13 % significantly related).	N/A	

Study/Author	Costs		Energy Benefits		Non-energy Benefits (NEBs)		Persistence Assumptions	
PECI/DOE, Deficiency Database (1996)	Moderate	Categorized as Assessment or Implementation. Included consultant, contractor, and building staff time, as well as parts and lease costs for monitoring equipment. Did not include "research" related costs.	Moderate	"Potential" energy savings reported. A combination of standard engineering calculations and DOE2 building simulations, with short-term diagnostic monitored data used to inform the calculations or model.	Moderate	Only includes extended equipment life, which is the most easily quantified effect. Categorized as extended equipment life through reduced hours of operation and through reduced short cycling. Calculated based on assumptions of reduced hours, reduced lifetime through short cycling, and nominal life.	N/A	N/A
Gregerson, RCx (1997)	Simple	Costs reported or estimated by each Cx provider. Costs include Cx fee, monitoring costs, and the cost of implementing measures except for in-house facility staff time during normal working hours.	Moderate	Project documentation may have utilized engineering calculations, models, or pre- and post-consumption measurement to quantify savings. Report notes that rigor with which energy savings were calculated varies significantly.	N/A		N/A	
PECI, Brochure (1997)	Simple	Cost range and median cost.	Simple	Savings range by building type. Conducted phone interviews.	Moderate	Identified NEB quantitatively for many different categories	N/A	

Study/Author	Costs		Energy Benefits		Non-energy Benefits (NEBs)		Persistence Assumptions	
Altweis (2001)		N/A	Complex	Used engineering calculations to estimate energy used with and without identified deficiencies. Provided *Most Likely* and *Least Cost Solution* scenarios, depending on assumptions for what would have occurred absent commissioning.	Moderate	Used simple calculations and extensive assumptions to estimate impacts to factors such as lost productivity, lost sales due to late building completion and equipment replacement. Provided *Most Likely* and *Least Cost Solution* scenarios, depending on assumptions for what would have occurred absent commissioning.	Simple	Lifetime assumed by measure and benefit (most are first-year impacts or flat over assumed lifetime).
Heinemeier, Schools Cx (2004)		N/A.	Simple	Comparison of monthly utility bills (electricity and gas (kBtu) per square foot), between commissioned and uncommissioned buildings (well matched pair or large sample size recommended), also comparing commissioned buildings with benchmarks (e.g., CBECS).	Moderate	Comparison of well-defined metrics collected during construction and operation phases, between commissioned and uncommissioned buildings (well matched pair or large sample size recommended).	Simple	Many benefits are first year. Persistence not addressed.

Study/Author	Costs		Energy Benefits		Non-energy Benefits (NEBs)		Persistence Assumptions	
Mills, Meta-analysis (2004)	Moderate	Cx and RCx: includes Cx provider fee, Cx coordination costs of other parties Cx: Does not include resolution cost for "quality assurance" findings or cost to fix design flaws RCx: Includes resolution cost	Moderate	Project documentation may have utilized engineering calculations, models, or pre- and post-consumption measurement to quantify savings. 58 % of RCx and 28 % of Cx projects verified measures to be implemented.	Moderate	First cost non-energy savings ($), and ongoing labor cost savings (type, labor hours saved), and includes a list of other NEBs (Y/N, $)	Simple (number taken from other studies, which are more complex)	Persistence data collected where available from other studies (LBNL, TAMU)). Used their methodology (see Persistence chapter of this report). For the majority of buildings, persistence or measure life was not addressed. [11]
SBW, Northwest Cx & RCx (2004)	Complex	Includes incremental fee increases, travel expenses, and resolution costs to each party, as reported by respondents.	Moderate	Used project documentation to identified significant and resolved issues, then used standard engineering calculations or parametric modeling to get savings.	Complex	Dollar value estimated three different ways based on telephone survey data with most conservative figure used.	N/A	
California Commissioning Collaborative's Cxdatabase.com (2004)	Moderate	Includes minor capital improvements as a cost of RCx. [12] Includes incremental costs to other parties	Simple	Respondent provides info for energy-savings calculations for each finding, not required to perform calculation. Persistence and avoided cost info optional. No standardized calculations for energy savings.	Simple	Respondents asked to identify which benefits they received, and given the option of entering a dollar value for the estimated avoided cost. No standardized calculations for avoided costs.	Not assessed	

[11] The fast payback times for Cx measures are most likely shorter than the period of erosion of savings.
[12] Allows owner to specify whether O&M staff participation is a cost or a benefit. Does not include resolution costs for "quality assurance" findings as reported by respondents.

IV. Recommendations, Decision Points, and Next Steps

Table 1.10 displays the 11 diverse studies reviewed in this report. The studies represent a large range of data collection, costs, energy benefit and non-energy benefit methodologies. Although this makes generalizations difficult, their collective efforts point to several recommendations moving forward, and several decision points to which any new study must attend.

Recommendations

1. Building commissioning data should be greatly diversified. In the majority of these studies, building information comes from only a few sources, like a handful of commissioning providers or a large university research department. It is thus unclear how well the findings of these studies will apply to the worldwide commissioning industry. Moving forward, an attempt should be made to gather building data from a much broader base. To date, it has been difficult to collect data from diverse projects because owners do not tend to ask for (or pay for) this kind of data on their own projects, and commissioning providers therefore do not gather it. Collecting commissioning data in a consistent way requires artificial injection of a research project or program to help standardize the way data is gathered and reported by market actors.

2. A complex cost-benefit methodology may require continuous data collection throughout the commissioning project, extensive interviews, or both, to acquire a sufficiently detailed reporting of costs. The data required for complex, and sometimes even moderate, cost methodologies will be difficult to obtain with a retroactive data collection methodology relying solely on documentation. It is nearly impossible to determine from documentation costs that are not explicitly defined during the project. For example, a study may want to include in its cost calculation the cost to the contractor of coordinating with the commissioning provider. If this cost is not defined either during or immediately after the commissioning process it will not be included in documentation (although it may be obtained through a timely interview). As a result, retroactive studies relying mostly on project documentation are often forced to "take what they can get," a methodology which does not lead itself to a consistent definition of commissioning costs. *A study employing a complex cost methodology should facilitate data entry by using a collection methodology that allows respondents to easily enter their own data and thus helps avoid the need for retrospective information gathering based on project documentation. The use of an automated or semi-automated analysis tool that positions the effort for ongoing analysis should also be considered.*

3. Data validation is an important aspect of any cost-benefit methodology. In cases where data is not verified, the accuracy of the cost-benefit results may be at risk.

Decision Points in Creating a Cx/RCx Cost-benefit Methodology

Creating an appropriate and feasible commissioning cost-benefit methodology that achieves the goals of the project requires careful planning around some key decision points. Ultimately, these decisions lead to a methodology that can have a range of levels of effort to collect and analyze data, as is shown in this chapter. The following key decision points emerged during this analysis of cost-benefit methodologies.

General

- What is the goal of data collection and who is the expected audience?
- What data and format are appropriate to the study goals and audience?
- What resources do researchers have available to them? This includes both financial resources as well as current and potential data sources.
- How important is verification of data? (Possible levels: reasonableness check, oversight of energy and non-energy benefits calculations, and verification for persistence.)

Data Collection

- Will the study be a one-time event that looks retrospectively at past projects, or will data collection and analysis occur continuously with current and future projects?

Costs

- Should the cost to resolve problems identified by the commissioning provider be counted as a cost of commissioning? If these resolutions are major design changes, should they be counted as a cost of commissioning?
- Should the commissioning-related costs of designers, contractors, and operating staff be counted as costs of commissioning?
- Are tasks performed by a commissioning provider that are out of the scope of commissioning counted as a cost of commissioning? For example, designers are generally tasked with developing the design intent documents. If the designer does not complete these documents, but the commissioning provider must have a complete set to functionally test the systems against, then often the commissioning provider will complete the task.
- Are costs treated differently for new construction commissioning and retrocommissioning?

Energy Benefits

- Will the methodology be whole building or measure based?
- Will the methodology require monitored data or rely on calculations, and will calculations be validated by monitored data?
- How will measured data be collected (e.g., utility bills, dataloggers, or trends from the building automation system)?
- How will it be tracked that identified measures are implemented?
- Will standardized calculations be used, or guidelines for calculations or modeling?
- What standardized documentation must be collected to support modeling or calculation?
- How will persistence of savings be estimated or verified?

Non-Energy Benefits

- Will an attempt be made to quantify the financial consequences of non-energy benefits?
- If not, how will non-energy benefits be reported and verified?
- If so, will the financial non-energy benefit be self-reported, or will a verification methodology be employed?

Next Steps

This chapter has described and compared how different studies have tackled creating a cost-benefit methodology for commissioning. Going forward, a standard cost-benefit methodology for an international audience will be created and populated as a part of the new IEA Annex 47. This effort will begin with discussions on how the US Department of Energy and Annex 47 members wish to proceed with the decision points listed above. These decisions must be made with an understanding of the level of funding and effort each country can contribute to gathering data. The first meeting of Annex 47 in Fall 2005 will begin this international planning effort to move the creation of a cost-benefit methodology forward.

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Chapter 2: Review of Persistence of Commissioning Measures in New and Existing Buildings

I. Introduction

In recent years the topic of persistence of benefits has gained more interest both for existing building retrocommissioning and new building commissioning. Several studies have been performed and published examining both aspects of this topic. This review will summarize the key results of these studies. The categories presented are persistence of commissioning measures in existing buildings, persistence of commissioning measures in new buildings, strategies for improving persistence in new and existing buildings, and related reports. This topic is relatively new, and the only relevant projects identified in the literature to date involve a total of 37 buildings as noted below:

- 10 Retro Commissioned Buildings at Texas A&M University – Turner et al. (2001) and Claridge et al. (2002, 2004)
- 8 Retro Commissioned Buildings in Sacramento, California – Bourassa et al. (2004)
- 8 Retro Commissioned Buildings in Oregon – Peterson (2005)
- 1 Retro Commissioned Building in Colorado – Selch and Bradford (2005)
- 10 Commissioned New Buildings – Friedman et al. (2002, 2003a, 2003b)

Since the total literature identified consists of published papers and reports from only five projects directly related to persistence, the summaries presented for each project are considerably more detailed than is customary in a literature review.

II. Persistence of Commissioning Measures in Existing Buildings

10 Buildings at Texas A&M University

A study was performed in 2000 to evaluate the persistence of savings in 10 buildings on a university campus three years after the buildings participated in retrocommissioning (Turner et al. 2001). The objectives of the study were to determine quantitatively how much savings degradation occurred and the major causes of any observed degradation. The investigation did not focus on the detailed measures implemented in each building but rather on the degree to which the measures implemented in the retrocommissioning process had been maintained, as indicated by examination of energy use data, the retrocommissioning reports, and the control settings in place on the main energy management control system.

The study was conducted in five major parts. First, buildings were selected to be studied. Second, savings calculations were performed based on energy usage data from the different periods needed. Third, field examination and commissioning follow-up was conducted on two buildings in which major savings degradation occurred. Fourth, operational and controls changes that could have contributed to changes in building performance after retrocommissioning were identified. And fifth, calibrated simulations of some of the buildings were performed to verify the effects of the identified changes on energy consumption.

A preliminary group of 20 buildings which had been commissioned in 1996 or 1997 was initially selected. An office review of information on the retrocommissioning measures implemented and available information on operating parameters before and after retrocommissioning was then conducted. Based on this review, the 10 buildings with the most complete information concerning the retrocommissioning process and energy consumption data were selected. None of the buildings in this group received capital retrofits during the period 1996-2000. Five buildings were commissioned in 1996 and the other five were finished in 1997. In each of these buildings, commissioning measures were identified by the retro commissioning provider and then implemented by the provider, after receiving the concurrence of the building owner's representative. Since all 10 buildings were located on a university campus, they primarily consisted of classrooms, laboratories, and offices, with one volleyball arena.

The energy usage data for these buildings had been monitored and was obtained beginning with the period shortly before retrocommissioning and ending in 2000 when the study was performed. For comparison purposes, all of the energy data was normalized to a single year of weather data. Because the weather data for the year 1995 most closely approximated average weather conditions for the years studied, it was chosen as the baseline year. Energy use before and after the retrocommissioning process were compared. In this study savings from the retrocommissioning process were determined by using Option C of the International Performance Measurement and Verification Protocol, which determines savings using measured energy use at the whole facility level. This required that baseline models of the consumption be formulated for each major source of energy use in each building. Chilled water and hot water energy consumption were measured for each year, and three-parameter or four-parameter change-point models of cooling and heating consumption were determined as functions of ambient temperature using a modeling program.

The process of calculating the yearly savings required the development of five separate chilled water models and five hot water models for each building, one for each year, including the baseline model. The consumption and savings for each year were then normalized to 1995 weather by using the models for each year's data with the 1995 temperature data to determine the savings for each year. Electricity savings were determined without normalization since the buildings did not have chillers, and electricity consumption is not appreciably affected by ambient temperature.

Follow-up was performed on two buildings with significant savings degradation. This was done primarily through a field investigation of the buildings to determine what changes had occurred that would produce the changes. Equipment performance and EMCS control settings were examined to evaluate possible causes for degradation.

Information was then gathered on controls and operational changes that had occurred in the buildings during the period studied. This was done by examining the retrocommissioning reports and interviewing the engineers and maintenance personnel who had responsibility for each building. These interviews provided identifiable reasons for many of the changes in savings seen in the buildings.

In order to quantify the effect of each operational or control change identified, it was decided that the energy usage of the buildings would be modeled using a computer simulation program. The rough simulations would then be calibrated until they provided accurate representations of the actual energy use. These simulations would then demonstrate how much of an effect each control or operational change had on the building energy use.

Results

All ten buildings showed significantly reduced chilled water and hot water energy consumption since retrocommissioning, although the savings generally decreased somewhat with time. Eight buildings had larger HW savings in 1998 than in 1997 as a consequence of hot water loop optimization conducted in 1997 and final retrocommissioning actions. Overall the electricity consumption remained fairly constant, with three buildings showing small increases in consumption (negative savings). The average electricity savings for the 10 buildings from 1997 to 2000 were 10.8 %. Figure 2.1 and Figure 2.2 show the chilled water and hot water savings trends for the years following the building retrocommissioning.

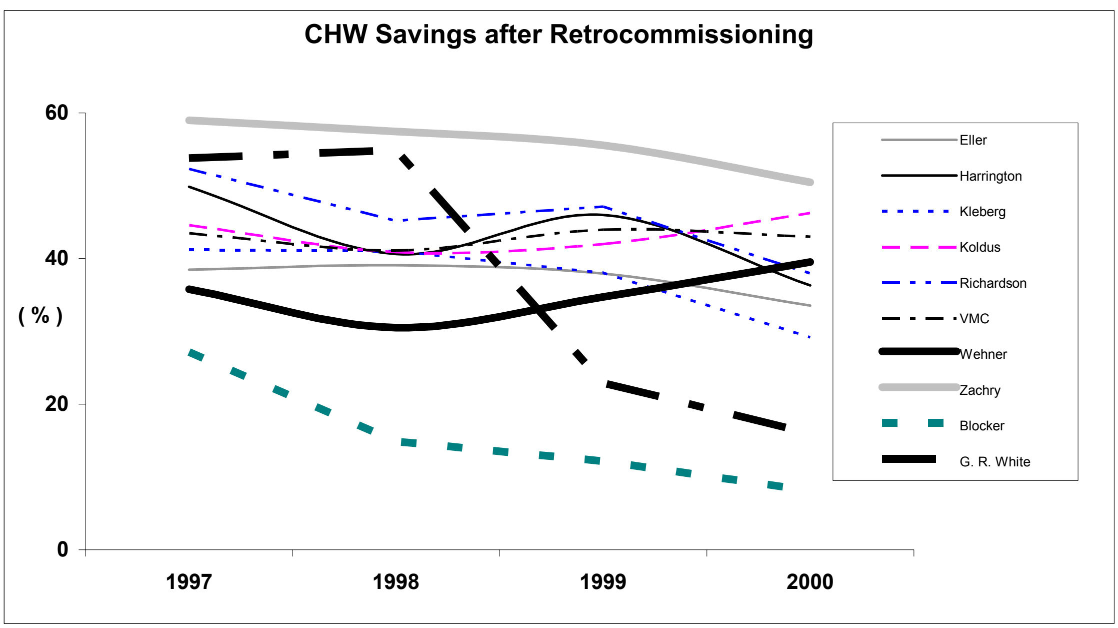


Figure 2.1. Chilled water savings persistence after retrocommissioning.

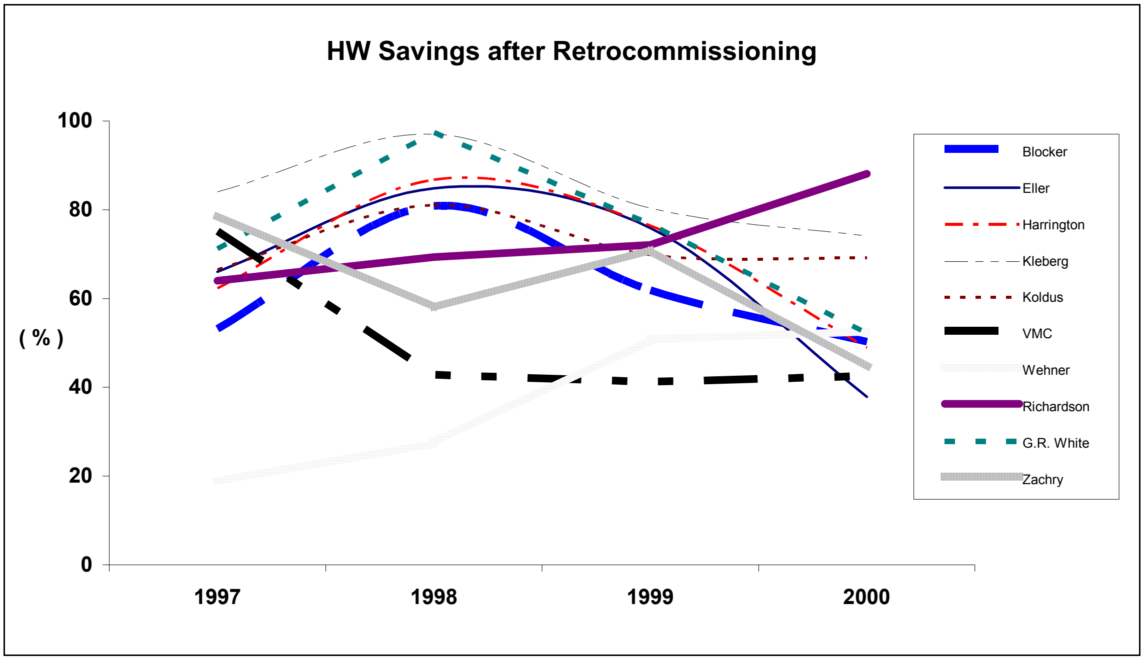


Figure 2.2. Hot water savings persistence after retrocommissioning.

Overall, chilled water savings for the three years following retrocommissioning averaged 39.3 % of the pre-commissioning baseline. Eight of the buildings showed good persistence of savings for chilled water (less than 15 % change during the 3 to 4 years after retrocommissioning), while the other two displayed significant degradation. The Blocker building had 19 % degradation, and the G. R. White Coliseum had a dramatic savings degradation of 38 %.

Hot water consumption was reduced significantly in the years following retrocommissioning, but the savings fluctuated widely from year to year. Savings increased from 1997 to 1998 in most buildings due to optimization in the hot water loop in 1997 and some ongoing retrocommissioning work. The 10 buildings averaged hot water savings of 65.0 % after retrocommissioning.

Based on the historic campus energy costs of \$4,42/GJ (\$4,67 /1 x 10^6 Btu) for chilled water, \$4,50/GJ (\$4,75/1 x 10^6 Btu) for hot water, and \$0.02788/kW·h for electricity, the cumulative savings from retrocommissioning in these 10 buildings were \$4 439 000 for the period 1997 - 2000. Only three buildings had year 2000 savings greater than 1998 savings, and the increase in two of these was about 2 % of baseline consumption, which is well within the range of normal year-to-year variation. The savings of the other buildings decreased.

Follow-up investigations of the two buildings with significant savings degradations revealed serious equipment malfunction and controls failure. In the Kleberg building, two chilled water control valves were found to be leaking badly, and combined with a failed electronic to pneumatic switch and high water pressure, caused low discharge temperatures and continuous reheat operation. In addition, failed sensors caused the outside air dampers to remain fully open, and leaking damper actuators in a number of

VAV boxes resulted in simultaneous heating and cooling. The G. R. White Coliseum was found to have a controls malfunction resulting in simultaneous heating and cooling, with two of the thirteen air handling units operating in heating mode, while the rest operated in cooling mode. These equipment and controls problems in these two buildings were the primary causes of the savings degradation observed. Because these problems did not result in comfort problems in the buildings, they may have gone undetected had the energy consumption not been monitored and compared with previous data.

The energy management control system settings were evaluated for the buildings to determine why the changes in savings occurred. Three major control settings were examined: cold deck or cooling discharge temperatures, hot deck temperatures, and static pressure settings. The cold deck or cooling coil discharge temperatures were reset during retrocommissioning to save chilled water consumption. It was found that for eight of the ten buildings in 2000, the temperatures had been lowered and were requiring more cooling. This led to chilled water savings degradation, particularly in the Blocker building. Five of the ten buildings had dual duct systems, and of these five, three of the hot deck temperature set points were at different values in 2000 than they had been upon completion of retrocommissioning. This resulted in more hot water consumption. Static pressure set points affected chilled water, hot water, and electricity consumption. Of the nine buildings with variable air volume systems, only one (Koldus) still had the same static pressure set point in 2000 that it had been set to during retrocommissioning. The other buildings were requiring more static pressure, and therefore using more energy. It is worth noting that the Koldus building showed no serious savings degradation of any kind in this study.

Data were gathered from engineers and maintenance personnel to attempt to verify the controls changes and explain them. It was found that the G. R. White Coliseum, which saw significant savings degradation in chilled water and hot water savings, had experienced malfunctions in air handling unit controls that caused simultaneous heating and cooling to occur throughout the year. Almost all of the savings degradation for this building could safely be attributed to these problems. It was also found that the Kleberg building had experienced some significant equipment problems that could explain some of the degradation in savings that occurred. No other building was reported to have experienced equipment problems of the same caliber as these two cases, but controls changes in the other buildings were verified through investigation. With the assembly of this type of information, simulated calibrations could be made for the buildings. Lack of data and other problems such as the one mentioned for the G. R. White Coliseum. White allowed only five of the ten buildings to be simulated. Three simulations were performed for each of these buildings, one for the pre-commissioning period, one for the year after retrocommissioning, and one for the year 2000. Factors considered in the simulations included control settings changes, operator overrides on the controls, and physical changes in the system such as broken or repaired valves, sensors, etc.

Detailed simulations of the control changes in Eller O&M, Harrington Tower, VMC Addition and Wehner showed that the RMS difference between the changes observed between the post-commissioning periods and year 2000 was only 1.1 %, suggesting that the changes in savings for these buildings were almost entirely due to the control changes identified.

Overall, equipment malfunction and changes made in cold deck and hot deck temperature settings following retrocommissioning were the major reasons for changes in chilled water and hot water energy consumption and savings after retrocommissioning.

Table 2.1 is a summary of the money saved in the year 1998 as compared with the money saved in the year 2000 for each of the ten buildings examined.

Table 2.1. Cost Savings Calculations for the Year 1998 and the Year 2000.

				Year 1998 Savings				Year 2000 Savings
No.	Buildings	Type	Baseline Energy Use (GJ/y)	Energy Use (GJ/y)	Savings	Cost Savings		
					GJ/y	Each $/y	Total $/y	Total $/y
1	Blocker	CHW	24 218	20 605	3 613	$ 15 993	$ 76 003	$ 56 738
		HW	9 216	1 768	7 448	$ 33 533		
		Elec.	4 832	3 883	950	$ 26 477		
2	Eller O&M	CHW	32 311	19 687	12 623	$ 55 875	$ 120 339	$ 89 934
		HW	8 001	1 218	6 783	$ 30 539		
		Elec.	4 891	3 675	1 217	$ 33 925		
3	G.R. White Coliseum	CHW	19 911	8 979	10 932	$ 48 386	$ 154 973	$ 71 809
		HW	22 319	580	21 740	$ 97 875		
		Elec.	1 480	1 168	312	$ 8 712		
4	Harrington Tower	CHW	14 959	8 883	6 076	$ 26 895	$ 64 498	$ 48 816
		HW	7 276	964	6 311	$ 28 413		
		Elec.	1 666	1 336	330	$ 9 189		
5	Kleberg Building	CHW	62 534	36 894	25 640	$ 113 491	$ 313 958	$ 247 415
		HW	43 059	1 281	41 777	$ 188 086		
		Elec.	5 511	5 067	444	$ 12 380		
6	Koldus Building	CHW	23 173	13 703	9 470	$ 41 916	$ 57 076	$ 61 540
		HW	2 218	421	1 798	$ 8 093		
		Elec.	2 850	2 597	253	$ 7 067		
7	Richardson Petroleum	CHW	30 096	16 497	13 599	$ 60 191	$ 120 745	$ 120 666
		HW	19 230	5 895	13 335	$ 60 035		
		Elec.	1 933	1 914	19	$ 519		
8	VMC Addition	CHW	43 143	25 406	17 738	$ 78 513	$ 87 059	$ 92 942
		HW	3 766	2 153	1 613	$ 7 260		
		Elec.	4 186	4 140	46	$ 1 286		
9	Wehner CBA	CHW	20 249	14 073	6 177	$ 27 339	$ 47 834	$ 68 145
		HW	14 130	10 250	3 880	$ 17 469		
		Elec.	2 555	2 446	109	$ 3 026		
10	Zachry Engr. Center	CHW	43 071	18 334	24 738	$ 109 496	$ 150 400	$ 127 620
		HW	8 098	3 408	4 690	$ 21 114		
		Elec.	7 502	6 793	710	$ 19 789		
Type			Totals				Year 1998	Year 2000
Chilled Water			313 666	183 062	130 605	$ 578 096	$1 192 884	$ 985 626
Hot Water			137 314	27 940	109 374	$ 492 417		
Electricity			37 407	33 018	4 389	$ 122 371		

* The baseline energy use data for two buildings were created based on the average savings of the other buildings because they did not have enough data.

**To obtain MMBtu/yr, multiply the number of GJ/yr by 0.9478.

Conclusions

Table 2.2 summarizes the savings history of this group of 10 buildings. The savings in 1998 following initial retro commissioning corresponded to average energy cost savings of 39 % for the 10 buildings. Savings decreased to 32.3 % over the next two years – still a highly significant level of savings.

Table 2.2. Summary of Savings History in 10 Retrocommissioned Buildings at Texas A&M

	Baseline Use ($/y)	1998 Cx Savings ($/y)	Persistence of Savings in 2000 ($/y)
10 Buildings	$3 049 487	$1 192 000 (39.1 %)	$984 516 (32.3 %)
8 Buildings	$2 195 307	$723 376 (32.9 %)	$666 108 (30.3 %)
2 Buildings	$854 180	$468 624 (55 %)	$314 408 (37 %)

Investigation showed that two of the buildings, G. R. White Coliseum and Kleberg, accounted for 3/4 of the total savings degradation, and both had experienced major equipment and controls malfunctions which were the primary causes of their degradation. Following correction of these problems, savings were restored to earlier levels. In the remaining eight buildings, savings changes were rather small, declining from 32.9 % to 30.3 % in aggregate.

All but one of the group of eight buildings had experienced at least some changes in EMCS control settings. To verify the impact of the EMCS changes on energy consumption, the calibrated simulation process was performed on the four buildings with the most complete data sets. Simulation was conducted for a pre-commissioning period, a post-commissioning period soon after retrocommissioning and for the year 2000 for each building. It was found that the changes in consumption observed following retrocommissioning in these buildings were consistent with those due to the identified controls changes, with an RMS difference of only 1.1 %. Control changes accounted for the savings increase observed in the Wehner Building as well as the decreases observed in the other three buildings. This suggests that the changes in savings these four were almost entirely due to the control changes.

Based on the results of this study of 10 buildings, it was concluded that:

- Basic retrocommissioning measures are quite stable,
- Savings should be monitored to determine the need for follow-up, and
- Steps should be taken to inform operators of the impact of planned/implemented control changes.

8 Buildings in SMUD Program in Sacramento

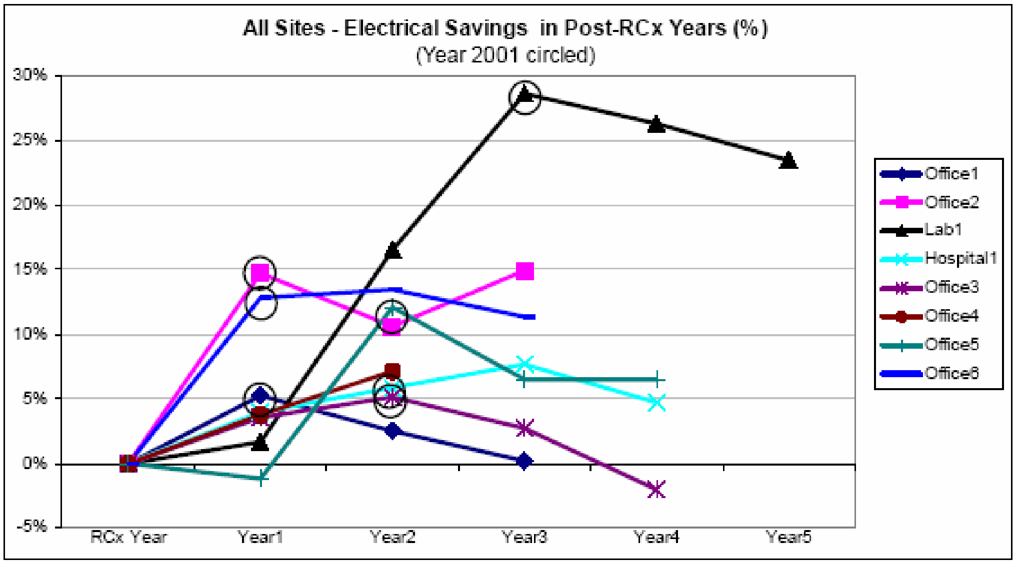
In 2003, a study was performed by the Lawrence Berkley National Laboratory (LBNL) on eight buildings that had undergone retrocommissioning through the Sacramento Municipal Utility District (SMUD) retrocommissioning program (Bourassa et al. 2004). The objective of the study was to determine the extent to which retrocommissioning measures were implemented, and the magnitude and persistence of energy savings achieved. Another objective was to see if the two primary goals of the SMUD retrocommissioning program had been met: reduced overall annual building energy consumption, and improved energy efficiency awareness and focus in the customer. The eight buildings selected for the study consisted of six office buildings, one laboratory, and one hospital. Four of the buildings participated in retrocommissioning in 1999, and the other four in 2000. In this program, the retrocommissioning provider worked with the building operators to develop the recommended measures. The measures selected for adoption were subsequently implemented by the building staff and/or contractors over a period of up to two years.

Energy Analysis

The energy savings obtained in the years following retrocommissioning were determined and compared. In order to be able to compare energy savings in the different buildings over the years examined, baseline energy consumption was established for each building based on pre-retrocommissioning energy use. Electricity use data were collected from monthly utility bills for each building. Four buildings also had metered data recorded at 15 minute intervals. Gaps in utility bills were filled from site records or regression analysis.

The energy consumption data were normalized to a common weather year and to a common billing cycle of 30.5 days. The savings were calculated using spreadsheets, based on the normalized data, which allowed for a simpler and more robust statistical comparison. Another set of savings was also calculated, based on the retrocommissioning report predictions. Adjustments were made for a capital retrofit in one of the buildings. The cost of retrocommissioning was also estimated for each of the buildings, based on three categories: SMUD's retrocommissioning costs, the site's retrocommissioning costs, and the retrocommissioning measure implementation costs. Based on the estimated costs and savings, simple payback periods for retrocommissioning at each of the sites were calculated and compared.

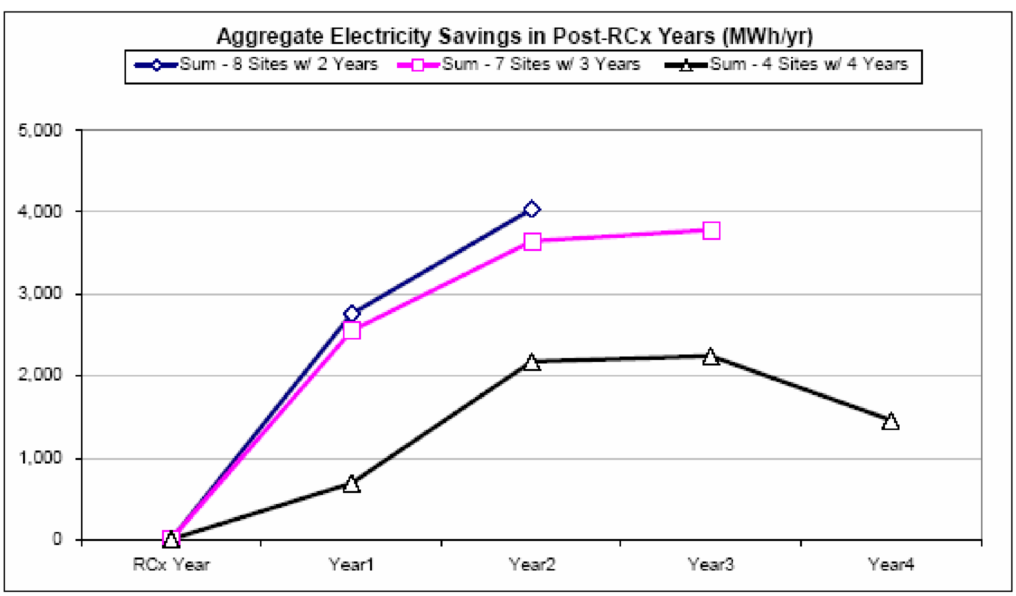
The electrical savings observed for each building over the years following retrocommissioning are shown in Figure 2.3.



Source: Bourassa et al. 2004

Figure 2.3. Electrical savings following retrocommissioning for each of the buildings.

The aggregate savings for the sites are shown in Figure 2.4. The buildings are grouped together according to the number of years of data available after retrocommissioning. Note that the "three year" line in the figure includes the data from the "four year" line plus data from three additional buildings, while the "two year" line simply adds data from one more building. Comparison with the data in Figure 2.3 suggests that the peak in year 3 may be largely due to the one building whose savings peaked in year 3.



Source: Bourassa et al. 2004

Figure 2.4. Plot of aggregate post-retrocommissioning electricity savings.

These plots demonstrate the observed trend in energy savings for the commissioned buildings. During the first two years the savings generally increased. This was expected because of the length of time needed for the retrocommissioning measures to be implemented. In the third year the savings began to level off, and the fourth year generally showed a declination in the electricity savings. A comparison with the predicted savings estimated in the retrocommissioning reports revealed that on average these reports underestimated the savings by 27.5 %.

The average electricity savings for all the sites over all the years was 7.3 % per year. Natural gas usage could only be obtained for four of the buildings. The savings for natural gas were considerably lower, but since Sacramento is dominated by cooling needs, the lower natural gas savings only reduced the average total energy savings in these four buildings to 6.1 % per year.

The payback periods for the retrocommissioning projects all proved to be attractive, with the longest period being 2.3 years. Table 2.3 lists the estimated costs, annual savings, and payback period for each site, as well as a price per square foot of the building.

Table 2.3. Costs, energy savings, and payback periods for the eight sites studied.
(Adapted from Bourassa et al. 2004)

Building	RCx Study Costs (Agent cost \$25k, balance incurred by site)	Estimated Measure Implmnt. Costs	Predicted Avg Annual Savings (\$)	Post-RCx Avg Annual Savings (\$)	Predicted Simple Payback	Post-RCx Simple Payback	RCx Study Costs (\$/m^2)	RCx Study & Implement. Costs (\$/m^2)
Office 1	$28 000	$1 710	$24 500	$13 000	1.2	2.3	2.05	2.15
Office 2	$26 500	$20 500	$21 900	$27 900	2.1	1.7	0.75	1.29
Lab 1	$26 000	$12 370	$64 800	$40 100	0.6	1.0	3.01	4.41
Hospital 1	$28 300	$11 180	$35 200	$30 900	1.1	1.3	1.18	1.61
Office 3	$25 400	$150	$6 400	$22 400	4.0	1.1	0.65	0.65
Office 4	$26 817	$8 380	$8 400	$22 600	4.3	1.6	0.86	1.18
Office 5	$26 817	$4 350	$9 100	$15 800	3.4	2.0	0.86	0.97
Office 6	$26 700	$3 000	$11 200	$48 600	2.7	0.6	0.97	1.08
All Sites Total	$214 533	$61 650	$181 600	$221 200	1.5	1.2	0.97	1.29

*To obtain costs in \$/ft^2, multiply the number of \$/m^2 by 0.0929.

Measure Persistence Analysis

A series of interviews and site visits were used to determine the persistence in the retrocommissioning measures recommended. The eight retrocommissioning reports recommended a total of 81 corrective measures, of which 48 were implemented. Of these 48, it was found that 81 % had persisted, in that they were still in effect at the time of the study. It was discovered that four of the measures had been abandoned completely, all of which were air distribution component recommendations. Five of the measures had undergone evolution by the building engineers because the original measures had not resolved the problems.

Surveys were given at the sites to determine attitudes regarding the retrocommissioning process, as well as its benefits. All of the sites reported that retrocommissioning was a worthy process. Four of the sites listed training as the primary non-energy benefit from retrocommissioning. The most cited downside to retrocommissioning was the time intensive nature of the process. All of the sites came out of the retrocommissioning process with ideas on how to retain the commissioning benefits over time, the most common solutions being preventative maintenance plans. All of the sites would undertake retrocommissioning again, but only two had potential internal funding.

Conclusions

Some important retrocommissioning process factors that this study identified were:

- The commissioning authority is most effective when he is both an expert and a teacher.
- Building engineers prefer to evolve the settings on a recommendation that doesn't work, rather than revert to the previous condition.
- Retrocommissioning appears to raise energy efficiency awareness.
- Retrocommissioning funds are constrained within building management budgets.

The energy analysis results showed:

- Analyses should not emphasize first-year savings because savings typically take two to three years to fully manifest.
- Energy savings persist to four years or more, although some degradation begins in the third year.
- The retrocommissioning energy savings predictions were reasonably accurate.
- Building managers lack tools for tracking energy performance.
- Retrocommissioning cost pay back was shorter than the apparent savings persistence.
- Retrocommissioning focused mostly on electricity savings and some natural gas trade offs in the savings occurred.

The study suggested several recommendations for the SMUD Retrocommissioning program:

- Develop measure implementation tracking agreements, possibly with inspections.
- Explore methods to conduct a three year post-retrocommissioning energy consumption analysis using the billing history.
- Develop simple Performance Tracking Tools for the building operators.
- Develop an extension to the program whereby participants are eligible for new incentives in year 4 to evaluate and update the retrocommissioning as necessary.

On the whole, the SMUD retrocommissioning program's two broad goals were met at the eight sites. Aggregate post-retrocommissioning savings were strong, peaking at approximately 4 420 MW·h and the program helped educate site staff about energy efficiency and the role operations and maintenance plays.

Oregon Case Study

A study performed in Oregon in 2004 examined eight Intel buildings that had been retrocommissioned in 1999 and 2000 (Peterson 2005). The buildings were located on the Intel Jones Farm and Hawthorn Farms campuses. Kaplan Engineering and PECI performed the retrocommissioning for these buildings through funding from Portland General Electric (PGE). At the time retrocommissioning occurred, it was estimated that electricity savings of nearly 3.5 million kW·h annually would result from the low cost energy efficiency measures (EEMs) proposed. The purpose of this study was to examine the energy usage of the buildings to determine what percentage of the original savings was still being achieved four years later. At the same time, it was desired to determine how many of the EEMs proposed were still being utilized.

Three of the buildings studied were located on the Hawthorn Farms Campus, and were designated HF1, 2, and 3. The buildings combined for a total of 59 457 m^2 (640 000 ft^2), and were served by a central chiller and boiler plant. HF1 had DDC control interfaced with pneumatic actuators, and the other two buildings were upgraded to DDC control in 2000. The remaining five buildings studied were located on the Jones Farm Campus, and were designated by JF. They combined for a total of 130 063 m^2 (1 400 000 ft^2), with over 40 major air handling systems served by two central chiller plants and two hot water boiler plants. Most of the spaces on both campuses were served by variable air volume (VAV) systems.

Three reports generated at the time of retrocommissioning were examined to determine what measures had been implemented. The current status of these measures was determined through random sampling, with functional testing or trending being used as appropriate. For HF1, the terminal reheat units were serviced at the time of retrocommissioning to ensure proper damper motion. At the time of this study, random sampling discovered no noticeable damper movement from full cooling to full heating in 60 % of the units. The savings for this measure did not persist, probably due to the aging pneumatic system. For HF 1, 2, and 3, retrocommissioning had modified outside air intake controls to allow for the economizing cycle to function. At the time of the study, random sampling revealed this measure to still be functioning. For the HF chillers, retrocommissioning had lowered the condenser water set point from 23.9 ^{o}C (75 ^{o}F) to 21.1 ^{o}C (70 ^{o}F), while raising the chilled water set point from 5.6 ^{o}C (42 ^{o}F) to 7.2 ^{o}C (45 ^{o}F). This measure was also found to be in operation at the time of this study.

For the Jones Farm buildings, air handling units and terminal boxes were scheduled at the time of retrocommissioning to reflect occupancy patterns, scheduling unoccupied hours as 6 PM to 6 AM on weekdays and all day on weekends. At the time of this study, JF3 was evaluated, and the control was found to be working fairly well, with only a couple of override issues. Additional savings opportunities for the JF buildings were also identified in this study, including air flow and scheduling opportunities and control overrides that needed adjustment. For the HF chillers, the leaving condenser water set point was lowered from 23.9 ^{o} C (80 ^{o}F) to 23.9 ^{o} C (75 ^{o}F) 67 ^{o}F at the time of retrocommissioning. The current study found the set point to be at 71^{o}F, still significantly lower than the original.

Overall at the Hawthorn Farms campus the ECMs were found to have been maintained, with the exception of the terminal unit reheat optimization in HF1. Of the original projected savings in the three buildings at Hawthorn Farms, 89 % of the electric savings and 0 % of the natural gas savings were still being achieved at the time of this study. In the five buildings at Jones Farm, the results were more mixed and less quantifiable. The recommended scheduling changes were still programmed at a high level, but it appeared that numerous control overrides at a zone or box level had been made. Some overrides may have been due to changes in space use (such as conversion to a lab), but in many instances conference and training rooms were maintaining occupied modes around the clock. The trending done on some of the variable speed air handlers showed little difference between day and nighttime airflow suggesting that terminal box scheduling was not having an impact on overall airflow.

Summary

Of the eight buildings retrocomissioned in Oregon in 1999 and 2000 quantitative findings were reported for three and qualitative findings for the other group of five buildings. For the three buildings on the Hawthorn Farms campus, totaling 60 000 m^2 in floor area, 89 % of the original electric savings were achieved in 2004 and 0 % of the natural gas savings were achieved in 2004. For the five buildings on the Jones Farm campus with 130 000 m^2 of floor area, the results were mixed and less quantifiable. It was found that scheduling changes were still programmed at a high level, but numerous control overrides at a zone or box level had been made.

Office Building in Colorado

A study completed in 2005 evaluated the persistence of recommissioning savings in a large office building in Colorado (Selch and Bradford 2005). Of the studies of this kind done to date, this study appears to have chosen the largest window of time over which to look at persistence. The office building was recommissioned in 1995, which resulted in verified savings of 14 % in electrical demand, 25 % in electrical use, and 74 % in gas use. In 2003, the building was again recommissioned, at which time the status of the energy conservation measures implemented in the initial recommissioning effort was evaluated.

The computation of savings was done in two ways. The overall energy use of the building for each year was obtained from utility bills. These data were then normalized to account for factors such as weather differences, changing occupancy patterns in the building, and added construction in the building. In this way the yearly energy use could be accurately compared to the baseline, pre-commissioned energy use. The other savings calculation method was an individual measure evaluation. Specific measures that impacted individual HVAC system components were examined. To perform the calculations, Options B & C of the International Performance Measurement and Verification Protocol (IPMVP 2001) were employed, Option B being used for individual measure evaluation, and Option C for whole building usage comparison.

Table 2.4 summarizes the results of the individual measures evaluation. The savings from the 2003 recommissioning effort are compared with the 1996 savings. To determine the persistence of savings, the percentage of 1996 savings achieved after recommissioning in 2003 was subtracted from 100 %. This is because it was supposed that the difference in achieved savings between the two recommissioning efforts represented those savings that had persisted.

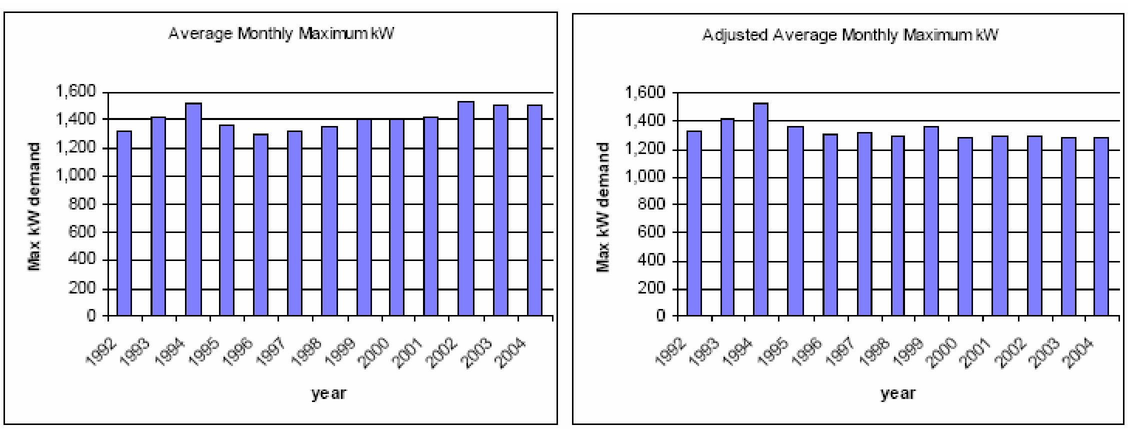
Table 2.4. Electric savings persistence summary.

	1996 Savings	2003
Electricity	20 % (1 600 000 kWh)	83 % Persistence (17 % Savings) (1 330 000 kWh)
Demand	14 % (219 kW)	86 % Persistence 12 % Savings (188 kW)
Gas	74 %	Complete persistence

As noted in Table 2.4, it was calculated that 86 % of the electrical demand savings had persisted, while 83 % of the electrical use savings had persisted. The results of the whole building energy use comparison appear in Source: Selch **and Bradford 2005**

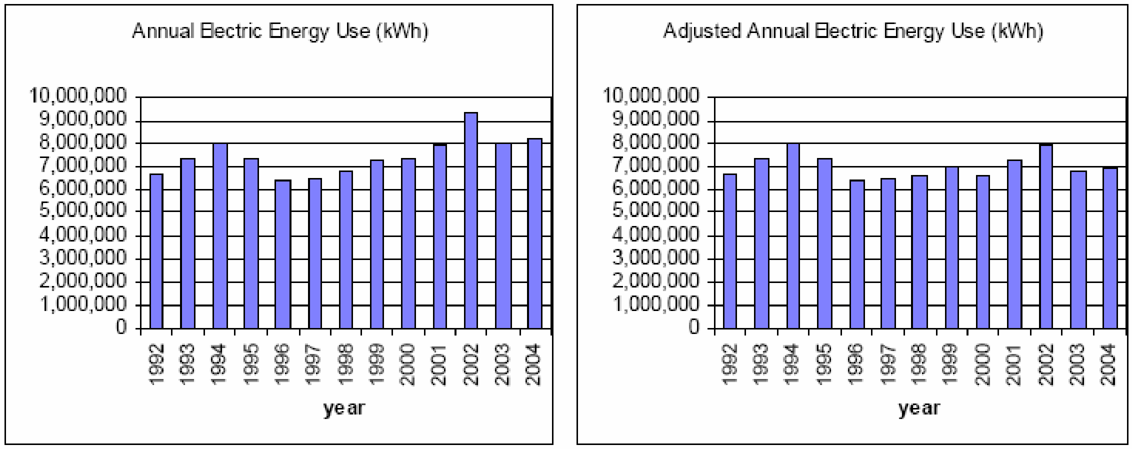
Figure 2.5 and Source: Selch **and Bradford 2005**

Figure 2.6. The left chart in each figure represents the raw values, while the right chart displays adjusted, normalized values.



Source: Selch and Bradford 2005

Figure 2.5. Annual electrical demand, raw and adjusted.



Source: Selch and Bradford 2005

Figure 2.6. Annual electrical use, raw and adjusted.

The annual demand and consumption values that were adjusted to account for changing conditions indicated that the savings achieved from recommissioning had largely persisted. This was concluded with greater confidence due to the corroboration of the independent measure analysis.

The study reported that a large majority of the energy savings measures implemented in the original recommissioning effort had persisted, as had their resultant energy savings. This was in spite of changing conditions in the building, including a complete change in operation staff. It was concluded that ECMs of this nature can persist for at least eight years even with limited support from operators and staff. However, it was noted that continued, on-going support to the building staff as part of the original recommissioning effort probably would have resulted in complete persistence of the savings achieved.

III. Persistence of Commissioning Measures in New Buildings

PECI PIER Study

In the summer of 2002, a study was completed that had begun in the fall of 2001 under a California Energy Commission Public Interest Energy Research (PIER) project (Friedman et al. 2003b). The purpose of the study was to examine ten buildings that were commissioned at building start-up in order to address the persistence of benefits from the commissioning process. This study drew qualitative conclusions about the persistence of new building commissioning, focusing on three issues: how well the benefits of commissioning persisted, the reasons for declining performance, and the methods that can be used to improve the persistence of benefits achieved through commissioning. A quantitative assessment of persistence by measure ("this measure has an expected persistence of X years") was outside the scope of this project, since a large number of buildings would have been required to determine the figures for each measure.

To evaluate the persistence of commissioning benefits on new buildings, the buildings first had to be selected. To qualify for the study, the facility needed to have been commissioned as a new building or major retrofit between two and eight years prior to the study. Due to the difficulty in finding such buildings with adequate commissioning documentation in California, five buildings were selected in the Pacific Northwest, and five more in California. It was not feasible to limit the study to buildings that followed the full commissioning process, from pre-design through final acceptance and post-occupancy, as described in ASHRAE Guideline 1 (ASHRAE 1996). The most completely commissioned and documented buildings were sought, but these typically did not include design-phase commissioning.

For each building, three to eight items were identified that were documented to have been fixed during commissioning. The changes and repairs made during commissioning generally fell into three categories: hardware, control system, and documentation improvements. Due to the focus on energy savings measures in the study, the hardware and control system changes with the greatest energy implications were of highest interest, as well as measures dealing with comfort and reliability. The amount of documentation available for each measure was also a driving force in measure selection. It was necessary to only evaluate those measures that had actually been implemented and documented. Routine maintenance issues or measures deemed static once corrected (such as equipment disconnected from the power supply) were not looked at. With the limited amount of time and funding for the study, it was necessary to focus on measures whose current status could easily be compared to the as-commissioned status and which would affect energy consumption. Because of the bias in selecting these measures, and the underestimation of savings persistence due to the limited number of measures considered, the results of the study were presented qualitatively.

For purposes of the study, it was decided that if the measure resulted in better performance than the pre-commissioning condition, then the measure was said to have persisted, even if it had been adapted to meet real operating conditions of the building. In some cases the persistence of a measure was somewhat subjective.

The people with the most knowledge about the control system at each site were interviewed. Some sites were identified for site visits, and for the others a second interview was conducted to discuss the current status of the commissioning measures. Six of the buildings were visited, during which the persistence of the selected commissioning measures was investigated, and the work environment and resources available to the operations staff were evaluated.

Results

It was found that the process of finding qualified buildings for the study in California was difficult. As mentioned above, qualified buildings were located more easily in Oregon, most likely because of the longer history of new building commissioning in the Pacific Northwest. California had numerous existing buildings involved in retrocommissioning projects, but new buildings having undergone commissioning at least two years earlier were sparse. For many of the commissioned buildings considered for the study, commissioning reports had not been written, so the information that could have been used by operations personnel to more efficiently operate the building essentially was lost. Often times in lieu of a report, the commissioning activities would simply be placed on a "punch list" for maintenance personnel to work on, who, when they had completed them usually did not document the changes. In other buildings the reports had been written, but were not readily available to the operations staff, having been filed away in storage and not easily accessible. In many cases where documentation did exist, it was not clear when or if the commissioning measures had been implemented, as they were noted as "recommendations" or "pending." These issues led to the conclusion that the term "commissioning" had been applied to a variety of different activities, including troubleshooting items and checklists, indicating a lack of consistency in the way the term was being applied.

Table 2.5 summarizes the commissioning measures studied and their level of persistence. A light gray square indicates that the measure persisted, while a black square indicates that the measure did not persist. A square split in half horizontally indicates that more than one measure was investigated in the category.

Table 2.5. Persistence of equipment and controls fixed during commissioning.

Source: Friedman et al. 2003b

	BUILDING (year commissioned)	DOCUMENTS			CENTRAL PLANT				AIR HANDLING AND DISTRIBUTION								PREFUNCTIONAL TEST					OTHER		
		Commissioning report on site	Commissioning report used	Control sequences available	Chiller control	Cooling tower control	Boiler control	Hydronic control	Economizer control algorithm	Discharge air temperature reset	Simultaneous heating and cooling	VFD modulation	Dessicant cooling	Duct static pressure	Space temperature control	Terminal units	Piping and fitting problems	Valve modification	Wiring and instrumentation	Sensor placement or addition	Sensor error or failure	Scheduling	Skylight louver operation	Occupancy sensor
California	Lab and Office 1 (1995)	no	-	yes	black	gray		gray							gray				gray			black		
California	Office Building 1 (1996)	no	-	yes	gray	black		gray	gray	gray				gray					gray		gray			
California	Office Building 2 (1996)	no	-	no				gray	black			gray		gray								gray		
California	Office Building 3 (1994)	yes	yes	no								gray	black	black	gray / gray		gray	gray						
California	Office Buidling 4 (1994)	no	-																			black	black	gray
Pacific Northwest	Office Building 5 (1997)	no	-	yes	black / black		black	gray / black	gray												black			
Pacific Northwest	Medical Facility 1 (1998)	yes	yes	yes	black													gray		gray	gray	gray		
Pacific Northwest	Medical Facility 2 (1998)	yes	yes	yes					gray	gray	gray					black / gray		gray			gray	black		
Pacific Northwest	Lab and Office 2 (1997)	no	-	yes					gray	gray						black					black			
Pacific Northwest	Lab and Office 3 (2000)	no	-	no				gray			gray			gray								black		

Across the ten buildings studied, patterns about the types of commissioning fixes that persisted emerged. For the fifty-six commissioning fixes selected, well over half of the measures persisted. It was not surprising that hardware fixes, such as moving a sensor or adding a valve, persisted. Furthermore, when control algorithm changes were reprogrammed, these fixes often persisted, especially when comfort was not compromised. Many design phase fixes may have persisted in a similar way, but these were not able to be studied since only one building was commissioned in the design phase.

The types of measures that tended *not* to persist were the control strategies that could easily be changed, such as occupancy schedules, reset schedules, and chiller staging. Four out of six occupancy schedules did not persist. Chiller control strategies did not persist in three out of four cases, most likely due to the complex nature of control in chilled water systems. The study of sensor issues was limited to major sensor problems that were corrected during commissioning, such as sensor failure or excessively faulty readings. With this selection bias applied, two out of five sensor repairs did not persist.

Among the commissioning measures implemented, a few cases involved technologies that were new or different from normal practice. Due to lack of documentation, these measures were not included in this study, but it was observed during the investigation that these measures generally did not persist. This was attributed to a lack of operator training for the technologies.

Discussion

The study suggested three possible reasons for lack of persistence among some measures. The first was limited operator support and high operator turnover rates. Operators often did not receive the training necessary or they did not have sufficient time or guidance for assessing energy use, and the training given new operators who came in after the commissioning was usually inadequate. The second reason involved poor information transfer from the commissioning process. For nearly every case studied, the commissioning report was either difficult to locate, or was not even located on site, which reduced the ability of building operators to review commissioning measures implemented. The third reason for lack of persistence was a lack of systems to help track performance. Operators spent most of their time responding to complaints and troubleshooting problems, leaving little time to focus on assessing system efficiency. Aside from this, lack of information and knowledge impeded the efficiency assessment by building operators.

The persistence of commissioning benefits was found to be highly dependent on the working environment for building engineers and maintenance staff. A working environment that was supportive of persistence included adequate operator training, dedicated operations staff with the time to study and optimize building operation, and an administrative focus on building performance and energy costs. Trained operators were found to be knowledgeable about how the systems should run and, with adequate time and motivation to study the system operation, these operators evaluated and improved building performance. In five buildings, operators participated in the commissioning process and came away with a good understanding of their systems. In addition, good system documentation in the form of a system manual served as a troubleshooting resource for operators at two buildings. It was noted that administrative staff can help enable a supportive working environment by placing high priority on energy efficient systems and operator training. Only a few of the buildings studied seemed to operate in this environment, and the measures investigated at these facilities had the highest rate of persistence.

Some of the measures simply persisted by default – no maintenance being required to keep them operational. If comfort issues were not a factor, or the measure involved programming buried deep within code, the measures tended to persist.

The study recommended four methods for improving persistence. First, operators should be provided with training and support. Especially with high operator turnover, adequate training is needed for benefits to persist, and a working environment with energy efficiency as a high priority is also beneficial. Second, a complete systems manual should be provided at the end of the commissioning process. This will serve as a reference for building operators, and will allow the systems knowledge gained from the commissioning process to be available over the long term. Third, building performance should be tracked. New building commissioning efforts should help to implement mechanisms for performance tracking, including what information to track, how often to check it, and the magnitude of deviations to address. Fourth, commissioning should begin in the design phase to prevent nagging design problems. Changes made on paper before construction has begun tend to be more cost effective and have higher levels of persistence.

The study concluded with a recommendation that more in-depth, quantitative studies be performed to investigate the life of commissioning measures and carry out cost-benefit analyses for new building commissioning. It was further recommended that a manual of guidelines for improving persistence be developed to give guidance and direction to building operators with regard to energy efficiency.

IV. Strategies for Improving Persistence in New and Existing Buildings

As a follow-up to the study of persistence of commissioning benefits for new buildings performed in California and Oregon, and the study of persistence of retrocommissioning benefits done at Texas A&M (both described previously), a report was issued in July 2003 addressed to building owners, managers, and operators suggesting methods for improving the persistence of commissioning benefits for both new and existing buildings (Mills et al. 2004). The report began by summarizing the key conclusions of both studies, namely that many commissioning benefits tend to persist fairly well, but that significant opportunities still exist for improving overall savings persistence. The report then proposed that an emphasis on certain key elements of energy analysis and efficiency would pave the way for long-term success in building operation and energy use. In particular, seven recommendations were discussed at length: design review, building documentation, operator training, building benchmarking, energy use tracking, trend data analysis, and recommissioning. A summary of the discussion of each of these topics is presented below.

Design Review

As many as one-third of major commissioning problems can be traced back to the design phase of the project and these problems often plague building operators throughout the life of the building. Allowing professional engineers to review the design while still in the design phase of the project is a cost-effective way to prevent future problems.

Correcting design problems on paper is easier and less costly than attempting to correct them once the building is completed. Some of the issues to be considered in reviewing a design are test port location, equipment accessibility, load calculations and minimum flow settings, control system sequences and point lists, and standard design details. The process of design review should begin as soon as possible to allow opportunity for correction.

Building Documentation

Good system documentation is not a common practice currently in the construction environment. While it may seem like a costly and time-consuming effort, this documentation is the best way to ensure that the knowledge base obtained during design, construction, and commissioning of the building is preserved, and will aid in maintaining commissioning benefits. The three most vital items to document are the final design intent, the sequences of operation, and the system diagrams. Other important documents include the operator's log, commissioning summary report, general description of facility and systems, as-built documents, detailed description of each system, location of all control sensors and test ports, and capabilities and conventions of the DDC system. The best time for this documentation to occur is during the construction phase of the building. For existing buildings, a good time is during a retrofit or recommissioning. The documentation should be compiled into a systems manual that is readily accessible.

Operator Training

Effective operator training will allow the benefits of building commissioning to persist, and will aid in preventing problems. Training opportunities exist for building operators during the commissioning process, through manufacturers and vendors, in operator certification programs, and using building documentation. It is also essential that new operators be trained sufficiently so that the knowledge gained by the previous operator is not lost. Some suggested training topics include: descriptions of equipment, equipment start-up and shut-down procedures, operation and adjustment of controls, review of system documentation, common troubleshooting problems, maintenance requirements and schedules, health and safety issues, special tools and spare parts inventory, and emergency procedures.

Building Benchmarking

Benchmarking refers to measuring the energy use of a building relative to other buildings, and provides a way to track energy use over time and compare it with the competition. This will allow building owners and operators to prioritize initiatives and improve energy efficiency. Several tools exist to aid in the benchmarking process. Two of these are the ENERGY STAR Portfolio Manager, which uses a number of factors to make meaningful comparisons with other buildings under different conditions, and the Cal-Arch Building Energy Reference Tool, which is a quick and simple tool for comparing energy use per square foot.

Energy Use Tracking

Tracking utility bills or metered data is an effective method for recognizing energy use problems that may not result in comfort problems, and therefore might not be noticed any other way. It is essential for continued energy efficiency and persistence in commissioning benefits. The energy use curves should be compared for different years to look for patterns, anomalies, and peaks and valleys. An Energy Information System is a useful tool for automating utility tracking. It saves time, provides immediate feedback, can gather additional data, and can allow access over the Internet.

Trend Data Analysis

DDC systems allow points to be trended over time. Knowing how to interpret these trended data is essential for identifying and correcting problems in building energy consumption and performance. The data should be examined regularly to determine if the system and its individual components are functioning as desired. Automated diagnostic tools exist to aid in this process, having automated capabilities in the following categories: data acquisition, archiving and pre-processing, detection, and diagnosis. Two tools available are ENFORMA and PACRAT. PACRAT can be used as an ongoing diagnostic tool.

Recommissioning

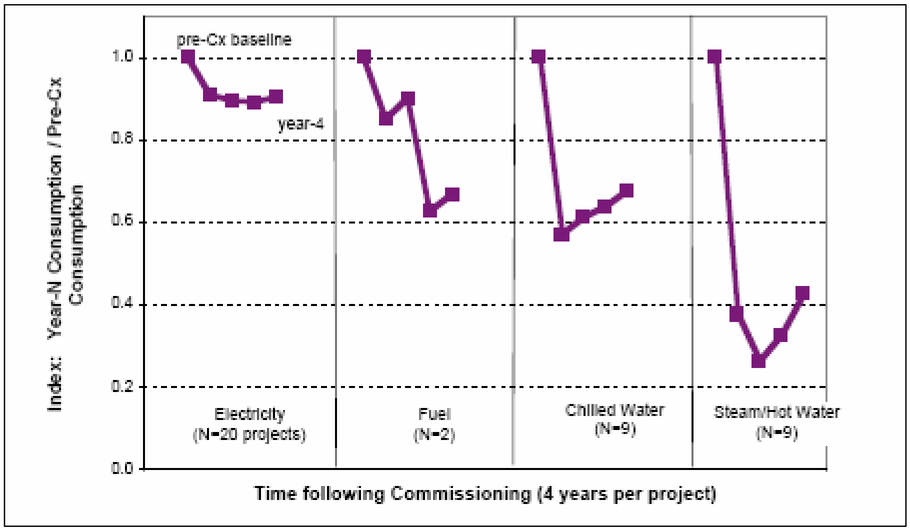
The process of recommissioning, especially when it draws on building documentation and previous commissioning activities, is very effective in maintaining commissioning benefits. The time to consider recommissioning largely depends on the effectiveness of operations and maintenance strategies and overall building performance. Commissioning can be performed by an outside commissioning provider when an outsider's view is considered helpful, or it may be done in house. In-house commissioning increases the knowledge level of those participating with regards to building operation. Continuous Commissioning is an ongoing commissioning process developed by the Energy Systems Laboratory at Texas A&M University that has the same general goal as retrocommissioning, but focuses strongly on the persistence of commissioning benefits.

The report concluded by reiterating the need to pursue the topics addressed during and after the commissioning process to maintain the benefits of commissioning over the long-term.

V. Related Reports

A report was compiled in 2004 that evaluated the cost effectiveness of commissioning in new and existing buildings (Mills et al. 2004). The largest study of its kind to date, it examined the results of commissioning for 224 buildings across 21 states. Among the existing buildings commissioned, a median payback period for commissioning was reported to be 0.7 years. For new buildings, this value was found to be 4.8 years. Both of these figures excluded non-energy benefits, which would increase the savings experienced.

While persistence of savings was not the primary focus of the study, it was examined briefly since it plays a role in determining overall savings. Figure 2.7 shows the persistence of savings results for 20 of the buildings in the study, with a four year period following commissioning in each building. The savings are indexed by a comparison of the year's consumption to the pre-commissioning baseline consumption. The savings are compared by category: electricity, fuel, chilled water, and steam/hot water.



Source: Mills et al. 2004

Figure 2.7. Emergence and persistence of energy savings (weather normalized).

An important factor noted in the report was the fact that in many cases of commissioning, the recommended measures were implemented gradually; indicating that the first year after commissioning was not the best year for calculating savings. On the other hand, it was also observed that after time some of the savings began to degrade due to changing building conditions, operations, or aging. As seen in the figure, the maximum value for savings was reached and subsequently savings began to degrade. This effect was smallest for electricity, but much more noticeable for chilled and hot water and steam.

With regard to persistence of commissioning benefits, the report concluded that tracking energy consumption for evidence of significant consumption increases is the most important means of determining the need for follow-up commissioning, and that while controls changes by building operators account for a portion of savings degradation, hidden component failures are perhaps the greatest culprit in persistence problems.

VI. Methodologies for Determining Persistence of Commissioning Measures and Energy Benefits of Commissioning

The retrocommissioning studies that provided a quantitative evaluation of the persistence of energy benefits of commissioning used variations on two different approaches to evaluate the persistence of energy benefits.

The study of 10 Texas buildings (Turner et al. 2001) used a variation on Option C of the IPMVP that normalized for weather differences between years by selecting a "normal" year of weather data in the sequence available that most closely met long-term norms. A suitable three-parameter or four-parameter regression model of the baseline year was created along with models of the performance of the building in each year evaluated.

Then the annual consumption for each year was determined by running the appropriate model with the appropriate year of weather data. The study of eight SMUD buildings (Bourassa 2004) used the same methodology, except that they used a long-term average weather year instead of selecting one of the available years of weather data. The Colorado study used a different approach, evaluating savings persistence with IPMVP Option C with baseline adjustments and IPMVP "Option B" was used to determine savings for specific measures in operation. The Oregon study did not specify how savings were evaluated.

The study of eight buildings in Oregon (Peterson 2005) and the Colorado building (Selch and Bradford 2005) used a different approach. These studies examined each of the measures that had been implemented and determined whether the measures were still in place and functioning. Peterson found that in three of the buildings, she could quantify the savings associated with measures that had been disabled after four years. It was found that numerous measures implemented in the other five buildings were still in place, but there were also numerous overrides and changes that had occurred as well. It was not possible to quantify the degree of persistence in these buildings. Selch and Bradford (2005) found that they were able to quantify the savings associated with measures that had been disabled.

The study of 10 new buildings that had been commissioned in Oregon and Washington (Friedman et al. 2003b) used a methodology that quantified the number of measures that were still in place, but it did not seem appropriate to try to quantify the energy savings associated with these measures. The four retrocommissioning studies all discussed the measures found to be still operating and those that had been changed. The Texas study used calibrated simulation to evaluate measures that had been changed. The other studies were not explicit in the methods used to evaluate the impact of measure changes.

VII. Summary and Conclusions

The results of studies from five projects related to commissioning, either in new or existing buildings, described above represent the extent of research that has been performed with regard to the persistence of commissioning benefits over time.

The savings in the buildings that were retrocommissioned generally showed some degradation with time. In retrocommissioned buildings, savings generally decreased with time, but there is wide variation from building to building. For the buildings where savings persistence was quantified:

- Savings persistence at the time of the study (3 to 8 years after commissioning) ranged from about 50 % to 100 % in all but one or two buildings.

- Average savings at the time of the study were about ¾ of the original savings.
- The most dramatic savings take-backs were caused by undetected mechanical or control component failures.

For the new buildings, well over half of the 56 commissioning fixes persisted. Hardware fixes, such as moving a sensor or adding a valve, and control algorithm changes that were reprogrammed generally persisted. Control strategies that could easily be changed, such as occupancy schedules, reset schedules, and chiller staging tended not to persist. It was also found that the extent to which persistence occurs is also related to operator training.

As is evident, the number of buildings studied in all of the papers described here represents a very small portion of commercial buildings that have undergone commissioning or retrocommissioning. More research is needed to:

- Develop a uniform methodology for determining commissioning persistence.
- Determine the persistence of savings from a broader sample of buildings.
- Develop simple tools for tracking performance of commissioning measures.
- Develop practical methods for owners and operators to better maintain commissioning savings.

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Chapter 3: Review of Automated Commissioning Tools for Buildings

I. Introduction

Commissioning is a quality control process developed to ensure that building systems operate as intended and meet their design intent. Commissioning is also an opportunity to achieve greater occupant comfort and energy-efficiency. As the value of commissioning is increasingly recognized, so is the need to facilitate this process. Researchers have worked on various approaches to aspects of this problem over the past decade; however, the availability of fully automated commissioning tools is limited. At present, the state of the art includes a number of automated and semi-automated commissioning tools that are being developed and tested at research institutions and universities with funding from utilities, industry, and government agencies. It is important to note that this review is based on publicly available information and therefore does not include tools in development by individual controls companies. As these technologies are proven, it is anticipated that the building control industry and energy services industry will be a key source as well as user of automated tools.

This chapter summarizes findings from a review of existing automated commissioning tools for buildings and related research. It builds on the Brambley et al. (2003) report on the use of automated tools for building commissioning. The second section gives an overview of the main tools to be discussed and includes tables that provide a more detailed description of the tools/prototypes and the key functions they are designed to perform. Because market availability of such tools is very limited, several prototype tools are also included. Section three takes a broader look at related research, including several enabling tools, and provides key references for work in the area of fault detection and diagnostics because of its relevance to continuous commissioning and the persistence of commissioning benefits. Finally, the chapter concludes with an overview of the barriers to automated commissioning and some recommendations for future work. Images of the tools discussed in this chapter can be found in the Appendix to this report.

II. Automated Commissioning Tools

The automated commissioning tools developed to date can broadly be categorized as:

- Tools to evaluate the performance of systems, or
- Tools that automate other aspects of the commissioning process.

These tools, which have been developed for a variety of conventional HVAC systems, address various aspects of initial commissioning and recommissioning/ongoing commissioning. Furthermore, they have been developed for different end-users in mind.

The first type, tools for performance evaluation, can be classified into tools for passive testing and for active testing. Passive testing involves using the control system to monitor and record sensor readings and control signals. It is non-invasive, monitoring the system under normal operating conditions. Data analysis methods are then applied to the collected data. Active testing involves injecting test signals that artificially change the system operation so as to exercise the system over its operating range. It is a means to extract a greater amount of information over a shorter time than in the case of passive testing but is invasive and more expensive to implement (Visier et al. 2005).

A common thread among many of the tools is the use of energy management and control systems (EMCS) or building automation system (BAS) for various functions, ranging from providing historical data to real-time control information. Building control systems have the capability to collect and store large amounts of time-series data; however, its use in that format has been quite limited because of the difficulty of extracting useful information. In response, open protocols such as BACnet greatly increased in the 1990's and diagnostic tools emerged in the late 1990's providing varying levels of monitoring capabilities. Friedman and Piette (2001) presented a review of emerging diagnostic tools that used EMCS data in either a manual or automated tool. Since that time, researchers have continued to pursue the automation of diagnostics, developing a number of tools that use data from the EMCS. And although the increasing availability of EMCS over the last ten years has resulted in greater access to operational data and a means to manipulate system operation, data-handling schemes are not standardized. In most cases, data configuration must be developed for each individual project, which is expensive.

Tool Selection

Although all of the commercially-available automated commissioning tools discussed in this review are US products, international research on automated commissioning has increased significantly in recent years. This review presents tools presented in major conferences, including the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) national meetings, the International Conference on Enhanced Building Operations (ICEBO), and the National Conference on Building Commissioning (NCBC). The international commissioning tools/prototypes presented in the review are limited to those developed and tested as part of the International Energy Agency's ECBCS Annex 40, focused on Commissioning of Building HVAC Systems for Improving Energy Performance. These tools included guidelines on commissioning procedures as well as prototype software that can be implemented in stand-alone tools or embedded in building energy management systems. Details on the annex tools described in this review are available in the final report and CD, downloadable from www.commissioning-hvac.org.

In most cases, tool development progresses from lab-tests to field-tests then to production prototypes before being considered commercially-available. The automated commissioning tools listed below are presented in a category best describing their most recent development status. In total, three commercially-available commissioning tools and six prototypes were identified. The collection of tools described in this section represent current and emerging US and international automated commissioning tools, beginning with commercially-available products. A general description is provided along with the tool name, information on the funding organization(s) and the relevant publication reference. Commercially-available tools and prototype tools are designated below as C# and P#, respectively.

Commercially-Available Automated Commissioning Tools

C1. **ENFORMA**, commercialized in 1996, Architectural Energy Corporation, USA (with Electric Power Research Institute cost-share) (Frey 1999). ENFORMA is portable diagnostic solutions software that can be used in the commissioning of new or existing buildings. It is useful for developing commissioning plans, collecting data. It analyzes data using mode-specific performance rules and guidelines to detect and report faults. It also generates visualization aids to help users identify installation and operation problems and optimize operation of building systems. An add-on to this tool is **MicroDataNet Systems**, a wireless data acquisition product line that provides internet access to equipment data by means of spread spectrum wireless technology. Other features include automated metrics.

C2. **Performance and Continuous Recommissioning Analysis Tool (PACRAT)**, commercialized in 1998, Facility Dynamics Engineering, USA (Santos and Brightbill 2003). PACRAT is designed to review recorded meter data and other operational data and perform diagnostic checks for system problems, poor performance and energy waste using a combination of detection methods, including visualization tools, historical process data, expert rules, and a cost analysis. It analyzes trend data to provide an ongoing baseline of building performance. Diagnosis is based primarily on expert rules.

C3. **Virtual Mechanic,** commercialized in 1996, Field Diagnostics Services, USA (http://www.fielddiagnostics.com). The Virtual Mechanic was developed as an embedded diagnostic tool for refrigeration equipment. It provides datalogging, calculates air conditioning performance indices that are the basis of the fault detection algorithm, provides alarm notification, and generates reports and analyses.

Automated Commissioning Tool Prototypes

P1. **Whole Building Diagnostician (WBD)**, pilot projects since 1998, Pacific Northwest National Laboratory, (US Department of Energy funding), USA (Katipamula et al. 2004). The WBD is a production-prototype software package for automated diagnostics in buildings. It has two main diagnostic modules that use sensor data from a building's direct digital control (DDC) system to identify problems and suggest solutions. The outdoor air economizer (OAE) diagnostician uses an expert rule set to detect and diagnose air-handling unit faults relate to outside air control and economizer operation. Multiple field-tests were completed.

P2. **Diagnostic Agent for Building Owners (DABO),** pilot projects since 2001, Natural Resources Canada (Choiniere et al. 2003). DABO, the Diagnostic Agent for Building Operators, is an EMCS-assisted commissioning tool using expert knowledge to identify these faults through the use of a hybrid knowledge-based system composed of an Expert System and a Case-Based Reasoning module. DABO is not yet available on the market but is being implemented in 15 demonstration sites in Canada.

P3. **CITE-AHU (**Commissioning the Installation and Technical Equipment-Air-Handling Unit), prototype and pilot project since 2003, National Institute of Standards and Technology, (US Department of Energy funding), French Center for Building Sciences (CSTB), France **(**Castro and Vaezi-Nejad 2005). CITE-AHU is an automated commissioning tool for air-handling units. It uses a library of test scenarios to automatically run functional performance tests and uses a rule-based approach to detect and diagnose faults in both constant and variable air volume systems. It also has the capability of automatically generating test reports. The prototype of this tool was developed in 2003 and it has been field tested in several four locations.

P4. **Semi-automated Functional Test Data Analysis Tool,** lab-tested prototype**,** Lawrence Berkeley National Laboratory, USA (STAC funding: California Energy Commission and US Department of Energy) (Xu et al. 2005). The tool is designed to automate the analysis of functional tests that have been performed manually. A set of functional test procedures has been designed to test the following air-handling unit components: mixing box, heating coil, cooling coil, supply fan, and return fan. Field measurements are entered manually into the tool by the user, avoiding the need for communication with the control system. The analysis tool uses simple mathematical models to define correct operation and uses expert linguistic rules and fuzzy inferencing to perform fault diagnosis. Field tests of this tool are due to take place in late 2005.

P5. **WebE**, prototype in 2003, VTT Building and Transport, Finland (Paiho et al. 2003). WebE, a tool developed by the Finnish team of IEA Annex 40, is a collection of modules for building energy management. Of particular interest in the continuous commissioning application is the ability to show likely causes for system malfunctions detected by the tool using sampling and data analysis

P6. **Control Logic Tracer,** Kajima Corporation, Japan (Shioya et al. 2003). The Control Logic Tracer is a tool developed by a Japanese research group as part of IEA Annex 40. It is designed to check the operation of the control logic by providing the designer or building operator with a means to visualize the operation of the control algorithm. The program reads operational data in extensible Markup Language (XML) format and displays the control sequence as a diagram that actively indicates the control path during operation.

Table 3.1 presents the tool name and the type of commissioning, lists the type of system targeted, lists the end-users that the tool is designed for, provides a description of the tools use, and gives an indication of the level of automation provided. Although the tools described in Table 3.1 are in varied stages of development, all have been lab tested and or field-tested. The list of prototypes is not comprehensive as there are many projects underway without published references but this list is representative of ongoing research.

Table 3.1. Description of Automated Commissioning Tools

Tool, Cx Type	**System**	**Main End-users**	**Description**	**Data Acquisition**	**Functional Tests**	**Fault Detection**	**Fault Diagnosis**
ENFORMA Initial Cx Retro-Cx	HVAC-Chiller, AHU diagnostics, Terminal Unit Controls performance Lighting performance	Facility Operators Facility Managers Energy Service Company Energy Managers	ENFORMA® Portable Diagnostic Solutions software ▪ creates a metering plan, determines the sensors needed ▪ time-synchronized building system data is obtained via the MicroDataLogger or using the EMCS ▪ software manages, calculates and filters the data, then generates diagnostic plots to assist in diagnosing facility and system problems MicroDataNet Systems provides wireless transmission of equipment data to the internet	Semi-automated	Manual	Automated	Semi-automated
PACRAT Continuous Re-Cx	Utility metering Chiller diagnostics Hydronic Distribution AHU diagnostics	Facility Operators Facility Managers Energy Service Company Facility Planners/ Designers Energy Managers	Performance and Continuous Recommissioning Analysis Tool- utilizing recorded system operational data to improve facility operations and planning. ▪ Diagnoses system problems and poor performance and identifies energy wastes ▪ Documents system operational parameters such as loads, energy use, and provides means to monitor and verify energy uses ▪ Summarizes and formats the data for effective visualization	Automated	Semi-automated	Automated	Automated
Virtual Mechanic Ongoing Cx	Refrigeration cycles	Field Engineers	A portable tool for data acquisition, fault detection and diagnostics for roof-top units ▪ monitors refrigeration cycles and interprets data in applications including air conditioning and refrigeration ▪ generates alarms, pages designated equipment and can shut off equipment	Automated	Semi-automated	Semi-automated	Semi-automated

Automated: [solid green bar] **Semi-automated:** [green-to-white gradient bar] **Manual:** [empty bar]

Tool, Cx Type					**Functional Tests**	**Fault Detection**	**Fault Diagnosis**
WBD Ongoing Cx	Electric and gas monitoring Chiller monitoring Economizer diagnostics	Building Operators	Whole Building Diagnostician- Dual module software tool using DDC sensors to analyze building performance ▪ OAE module- automated tool for continuous analysis of economizers ▪ WBE module- automated tool for continuous analysis of whole building or central plant energy consumption ▪ Provides potential solutions to users	Automated	Semi-automated	Automated	Automated
DABO Ongoing Cx	AHU, VAV diagnostics	Building Operator Energy Service Company Maintenance Company	Diagnostic Agent for Building Operators- Commissioning module ▪ Tool continuously monitors the building control data and stores it in a database ▪ Database serves as a server for reasoning algorithms that analyze data, perform automated tests of components or systems, identify and diagnose faults, and evaluate potential energy efficiency improvements ▪ Generates reports documenting results for end-users.	Automated	Semi-automated	Automated	Automated
CITE-AHU Re-Cx	AHU diagnostics	Building Operator Energy Service Company Maintenance Company	Commissioning the Installation and Technical Equipment-AHU-- Automated commissioning software for air-handling units ▪ Applicable to both constant and variable air volume systems ▪ Execute scenario software enables the development/storage of automated test library ▪ Data analysis can be run in real-time or as a batch process ▪ Faults detected and list of probable causes presented to user along with relevant sensor and control signal plots	Automated	Automated	Automated	Semi-automated

Automated: ■ **Semi-automated:** ▨ **Manual:** □

Tool, Cx Type	System	Main End-users	Description	Data Acquisition	Functional Tests	Fault Detection	Fault Diagnosis
LBNL Functional Perf.Tests	AHU diagnostics Mixing box, heating/cooling coils, supply/return fans	Building Owner/Operator Commissioning providers	Semi-Automated Functional Test Data Analysis Tool ▪ Manual entry of measurements via graphical user interface ▪ Analyze data, compare measured vs. expected performance ▪ Assess system performance, identifying likely causes of failure	Manual	Manual	Automated	Automated
WebE Ongoing Cx	Energy consumption monitoring	Building Operator Building Owner EMCS Supplier	Web-based tool to facilitate Building Energy Management ▪ Building information from National Building Register ▪ WebEtana - Energy consumption estimator ▪ WebKulu - Energy Consumption monitoring module ▪ Fault diagnostics and commissioning of building energy systems based on deviation of consumption from estimates and/or historical data	Manual	Manual	Automated	Automated
Control Logic Functional Perf.Tests	Control system	Building Operator EMCS Installer EMCS Designer	Graphical tool to check the sequence of operation ▪ Provides transparency of HVAC control logic ▪ Allows user to visualize control sequence over time ▪ Diagnose failures traceable to system control ▪ Provides useful information to correct operation or control failures	Automated	Semi-automated	Automated	Automated

Automated: [green bar] **Semi-automated:** [gradient bar] **Manual:** [empty bar]

I. Related Research

Although the number of automated commissioning tools is small, there are continued efforts underway to facilitate the implementation of the commissioning process and the development of new tools. Many researchers, including companies, are working to develop various tools to advance the market availability of automated commissioning tools. In addition to developing new technologies, this work includes the development of enabling tools and studies to advance the capabilities of diagnostic methods. The five tools described below are sample of resources designed to assist commissioning agents, planners and automated commissioning tool developers.

Enabling Tools

The first two tools presented in this section are more recent examples of a class of data management tools that enable easy data collection and improves data visualization capabilities. Two early examples of data management tools include the Enterprise Energy Management Suite (EEM Suite) and the Information and Monitoring Diagnostic System (IMDS). The EEM Suite, commercialized in 1998 (Itron, Inc., USA, http://www.itron.com), provides continuous display and manipulation capabilities for utility and EMCS data. It is a tool designed to aid energy managers in the visualization of system performance and is an example of a tool often referred to as Energy Information Systems. The IMDS prototype was first implemented in 1998 by Supersymmetry, LBNL, EN-Wise, C.Shockman, A. Sebald (CIEE, US Department of Energy Funding) (Piette et al. 2000). The IMDS was a high-quality metering and monitoring system intended for a sophisticated building operator or commissioning agent and was designed to demonstrate the benefits.

E.1 **EnergyWitness**, commercialized in 2005, Interval Data Systems, USA (http://www.intdatsys.com). It collects and archives data from multiple sources, including the building automation system (BAS) to visualize, detect, and diagnose faults. It is an on-site application.). This tool is one example of a class of data management tools that enable easy data collection and improves data visualization capabilities. Two early examples of data management tools include the Enterprise Energy Management Suite (EEM Suite) and the Information and Monitoring Diagnostic System (IMDS). The EEM Suite, commercialized in 1998 (Itron, Inc., USA, http://www.itron.com), provides continuous display and manipulation capabilities for utility and EMCS data. It is a tool designed to aid energy managers in the visualization of system performance and is an example of a tool often referred to as Energy Information Systems. The IMDS prototype was first implemented in 1998 by Supersymmetry, LBNL, EN-Wise, C.Shockman, A. Sebald (CIEE, US Department of Energy Funding) (Piette et al. 2000). The IMDS was a high-quality metering and monitoring system intended for a sophisticated building operator or commissioning agent and was designed to demonstrate the benefits. **Energy Expert**, commercialized in 2005, NorthWrite, USA (http://www.energyworksite.com). This tool enables near "real-time" response to unusual energy usage. It uses direct meter readings through an on-site gateway as input data. It provides data visualization, automated and manual fault detection and supports manual fault diagnosis.

E.2 **Cx Assistant**, Energy Design Resources (Pacific Gas & Electric Funded) (Sweek et al., 2004). This process tool assists the user to organize the commissioning process and provides tools to help define the appropriate scope for a particular project.

E.3 **MQC Matrix,** Kyoto University, Tonets Co., Japan (Nakahara and Kamitani, 2002). The MQC Matrix is also designed to facilitate the organization of the commissioning process. It structures each phase and step and provides drill down capabilities to store and retrieve relevant information, accessible by all parties.

E.4 **Commissioning Test Shell,** National Institute of Standards & Technology, (Castro et al., 2003). The test shell was developed as part of IEA Annex 40 to provide a means to test multiple commissioning tools using the same data. The tool interfaces to the Virtual Cybernetic Building Testbed, a building simulation/emulation.

E.5 **CACEA, ComIT,** Facility Dynamics Engineering, USA. CACEA is a design and cost management tool that can work in conjunction with ComIT. ComIT establishes a communications link to commissioning providers to enable the sharing of files and structuring of the commissioning process.

E.6 **Commissioning Test Protocol Library (CTPL),** Pacific Gas & Electric (Gillespie et al., 2001). The CTPL is a database of component, equipment, and sub-system level protocols. Over 600 protocols were reviewed and rated. The library includes a subset, providing: the test name, the conditions under which the test is to be performed, test duration, data to be gathered, method and location of measurements required, instrumentation and data acquisition requirements including measurement tolerance, results to be obtained including analysis calculations if required, specific measurable acceptance criteria and any notes to the user.

E.7 **CMU-BC prototype,** Carnegie Mellon University (Turkaslan-Bulbul et al.2005, Wang et al. 2004). The CMU-BC prototype is a system that models the processes and products of building commissioning. The first version of the CMU-BC prototype is a comprehensive implementation dealing with the AHU. It is an in-depth (comprehensive sets of attribute-value pairs), and evolutionary prototype (i.e., it can be expanded and become more inclusive). This prototype has been used effectively to undertake data translation between different automated applications, databases and product models, which lies at the heart of interoperability technology.

E.8 **Universal Translator,** Pacific Energy Center/PG&E. Is a translation tool « Rosetta stone » that prepares performance data from multiple sources for evaluation. This tool is publicly available, and has approximately 200 users.

E.9 **Energy Charting and Metrics**. PECI. Is an excel spreadsheet that provides flexible metrics and charts in a user-friendly format. It is nearing its pilot test and will be made publicly and freely available.

Table 3.2 provides more details on the nine enabling tools, presenting the tool status, its application, and targeted end users, and a description of its features.

Table 3.2. Description of Enabling Tools

Tool/ Status	Application	Main End-users	Description
EnergyWitness Commercially available 2004**Cx Assistant/** Commercially available 2004	All system data e.g., chillers, cooling towers, boilers, distribution loops, air handlers, and buildings Initial Cx Ongoing Cx	Energy Service Company Facility Planners/ Designers Energy Managers	Energy Witness has 8 modules: EWDataCollector and EWDataWarehouse- for data handling EWViewer- the user interface for visualizing data, monitoring systems, and performing diagnostics, includes EWIssuesTracker - for problem recording, tracking and communications; EWPhysicalPlant - the main diagnostic component for chillers, co-generation, etc., uses a mathematical model to compute operating cost and compares it to historical data; EWUtilityBilling - for cost-allocation, invoicing; EWPurchasedUtilities - for management of purchased utility bills; and EWPublisher- for web-distribution of web-based tool to facilitate organization of commissioning process ▪ Designed to provide project-specific info to design teams ▪ Enables user to evaluate probable commissioning cost, identify appropriate commissioning scope ▪ Provides sample commissioning specifications relevant to project
Energy Expert	All system data- whole building or sub-metered systems	Energy Managers Provided as a software service via Web to Building owners, Facility Operators Facility Managers	Energy Expert enables daily tracking of energy usage, including energy savings, and enables a near real-time response to atypical energy usage. Performance deviations are recorded when deviations are deemed statistically significant and exceed a user-defined cost threshold. The tool documents analysis results and also provides a means to evaluate persistence of energy savings measures.
Cx Assistant/ Commercially available 2004	Initial Commissioning	Designers	Web-based tool to facilitate organization of commissioning process ▪ Designed to provide project-specific info to design teams ▪ Enables user to evaluate probable commissioning cost, identify appropriate commissioning scope Provides sample commissioning specifications relevant to project
Standard Models of Commissioning Plans (SMCP)	All Cx Types	Commissioning Provider, Building Owners	A typical description of commissioning actions all along a project. Intended as a guideline to define the commissioning plan for a given project.
MQC Matrix/ Available 2005	Initial Cx	Designers	Microsoft Excel-based tool to facilitate organization of commissioning process ▪ Includes commissioning plan, other elements and references in a structured manner

Tool/ Status	Application	Main End-users	Description
Commissioning Test Shell/ Available in 2001	Tool development and testing	Tool Developers	Communications software that facilitates data transfer from BACnet speaking objects to a database ▪ Enables the comparison of multiple commissioning/diagnostic tools which view the same data
CACEA, ComIT/ Commercially available in 2000	Initial Cx / general	EMCS designer, Commissioning Agent	Controls and Commissioning Engineering Application ▪ Stores knowledge base of commissioning procedures, automates creation of procedures and creates graphical elements with links to issues, data, functional tests, etc. ▪ Enables the organization and sharing of system information through the use of a multi-level tree using a standard configuration ComIT- a collaborative commissioning tool that uses the internet to connect all Cx team members
CTPL/ Developmental Release 1.3.1, completed March 2003	All Cx types, various systems	Commissioning Providers	Commissioning Test Protocol Library, an informational database with four primary components: ▪ Document and protocol review database ▪ Library of 630 existing commissioning related protocols ▪ User protocol archive ▪ Protocol templates document
CMU-BC	All Cx types, AHUs	Programmers, Designers, Commissioning Providers, Facility Managers	Supports computer based applications by providing a complete library of descriptors and attributes of ▪ equipment, equipment components, and their properties ▪ measurable values and ranges for functional inspections ▪ measurable values and ranges for functional performance tests Supports interactive encoding of Cx measurements, their value ranges, and the production of documents and report, such as ▪ FPT protocols, reports, and instructions Interim and final Cx reports

Tool/ Status	Application	Main End-users	Description
Universal Translator	Data Acquisition and Analysis	Anyone managing building performance data	A translation tool that prepares performance data from multiple sources for evaluation ▪ Data is collected and imported into the software tool ▪ Corrections can be applied to data if needed ▪ Data is resampled to synchronize data interval ▪ Graphing tool provides visualization Data can then be used to identify performance issues.
Energy Charting and Metrics	Tracking building performance/ Data analysis	Building Operators RetroCx providers	A stand-alone batch tool linked to Microsoft Excel. The tool assists with performance tracking and the inter-relationships between data points.

Key References for Diagnostic Tools

In addition to the enabling tools, there are a large number of diagnostic tools with varied levels of automation. Much of this research has formed the basis for the analysis component of emerging commissioning tools, specifically tools designed for functional performance testing and ongoing commissioning. Using the operational data, various methods can be implemented to determine whether the system(s) are operating as intended.

Research relating to diagnostic tools has been performed both in the US and internationally. Katipamula and Brambley (2005a, 2005b) present reviews of methods for fault detection, diagnostics and prognostics for chillers and air-handling units. An earlier review by Friedman et al. (2001) also included a review of manual diagnostic tools. International efforts include products resulting from International Energy Agency ECBCS Annex 34, focused on Computer-aided Evaluation of HVAC System Performance, completed in 2000.

In addition to these, it is worthwhile to mention an ongoing project, the "Development, Implementation and Deployment of Automated Fault Detection and Diagnostics for Vapor Compression Equipment, which was started in June 2005 with a two year duration. The project team of Purdue University, Field Diagnostic Services, Ben Franklin Technology Partners, and Honeywell Inc. are working to develop tools that could be applied to several types of vapor compression equipment. It is anticipated that these development could automate portions of the commissioning/recommissioning process for certain types of equipment.

A more exhaustive list of references to methodologies and related tools (i.e., fault detection and diagnostic tools) is included in the bibliography.

The basic methods used for detecting faults in buildings include:

- Visualization tools for manual detection
- Models derived from design information and manufacturers' data
  - First-principles models
  - Semi-empirical models
  - Empirical models
- Models derived from process history
  - Reference comparison plots
  - Statistics reports
  - Benchmarking
  - Semi-empirical models
  - Empirical models
- Performance metrics (energy use, efficiency)
- Guidelines for correct operation, cost estimates
- Expert rules
- Modeled baselines
  - Quantitative methods

- Qualitative methods
- Physics-based methods

IV. Market Penetration

The market penetration of commissioning is gradually increasing, strengthened by the greater involvement of key players in the buildings industry, including: building operators, owners, managers, consultants, and builders. It is evident that as commissioning is increasingly applied, the need for qualified technical experts will increase. As stated in the review of cost-benefit methodologies, it is important to examine the role that automated tools have on improving the cost-benefit ratio. It is anticipated that the use of automated or semi-automated commissioning tools will enable more people to perform these functions in a more efficient manner than at present. Overall, there is good but limited anecdotal evidence showing the value of automated commissioning tools but there are few tools available and current and emerging tools need to be more robust to increase the potential applications.

Barriers

The main barriers to commissioning are that:

1. Commissioning is a manual, time-consuming task
2. Commissioning is seen as a cost instead of as an investment
3. Documented commissioning methods are currently limited to conventional HVAC systems
4. There is a lack of technical experts and tools for field optimization, commissioning, and data visualization
5. Information is lost between design and commissioning.
6. The lack of standardized data handling schemes increase project costs
7. Market planning during tool development is inadequate
8. Measures are not taken to ensure persistence of benefits

Potential Benefits

Because the current commissioning process is both time-consuming and expensive and there is a need to commission both new and existing buildings for improved energy performance, the value of these potential benefits is substantial. Many of the tools and tool prototypes described in this paper provide means to facilitate aspects of the commissioning process for particular HVAC systems; however, there is also a great potential for improving these tools. Some of the potential benefits of automation listed by Brambley et al. (1999) are shown italicized in Table 3.3. These potential benefits still exist and advances have been made. The table summarizes the current state of automated tools for commissioning, including limitations that could be addressed by further R&D.

Table 3.3. Potential Benefits of Automated Tools and Current State of Development

Potential Benefits	Current State of Automated Tools
Speed up the process of preparing a commissioning plan, ensure compliance with standards/guidelines, and help ensure consistency across projects.	Several enabling tools provide templates, guidelines and file-sharing features that can begin to address this goal. The current limitation is in the types of building systems covered.
Speed up the process of detecting and diagnosing problems with the operation of heating, ventilating, and air conditioning equipment and systems	Tools exist for a variety of conventional HVAC systems, however, due to the near-infinite variations in system designs and control algorithms, time and expertise needed for tool configuration is a limiting factor.
Improve quality of data handling by eliminating the possibility of introducing errors through manual data entry	Access to EMCS data is a valuable tool. Many proprietary formats still exist which impede data access, particularly for existing buildings.
Disseminate expert knowledge by embedding it in software tools, Ensure consistency in fault detection and diagnosis across buildings, projects and different commissioning agents	The embedded knowledge, combined with the increased transparency of system operation through improved visualization tools can greatly empower building operators
Disseminate expert knowledge by embedding in manufacturer's equipment.	Prototype embedded implementations of diagnostic tools have already being tested (Schein et al. 2003), with promising results.
Archive data electronically for future reference or use.	Tools developed that reside in the EMCS or having good data access can perform added functions such as automatically generate necessary documentation, provide access to historical data to show how system use has progressed over time.

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Chapter 4: Review of Needs and Challenges in Commissioning Zero Energy Buildings

I. Introduction

This section reviews the particular issues that apply to the commissioning of aggressively low energy buildings and that can be expected to apply to buildings that approach zero energy consumption. A literature review of commissioning and operational experience with existing buildings that were designed to have low energy consumption has been undertaken. Key findings from a number of case studies are reported and generic conclusions with implications for R&D are presented.

Based on both recent low energy designs and current thinking, buildings that approach zero energy consumption can be expected to have most or all of the following characteristics:

- Dramatically reduced electrical and thermal loads
- Remaining loads met by solar (photovoltaics and solar-thermal)
- Very efficient components and subsystems
- Unconventional systems
- Close integration of systems:
  - HVAC
  - Lighting
  - Daylighting and facade
  - On-site generation
- (Near-)optimal control

Many of these characteristics are found in recently constructed 'green' buildings, especially those designed to achieve Gold and Platinum Leadership in Energy and Environmental Design (LEED) ratings. As regards commissioning, 'Fundamental Building Systems Commissioning" is required for all LEED-rated buildings. An additional LEED point is available for 'Additional Commissioning', which makes it more likely that a more comprehensive commissioning process will have been followed for Gold and Platinum buildings. Since these buildings typically have more innovative systems in order to meet their more aggressive energy consumption targets, they are the subjects of choice for the study of issues relating to the commissioning of very low energy buildings. Unfortunately, there is relatively little detailed information available that is relevant to the commissioning of these buildings. For example, almost all of the case studies on the US Green Building Council website[13] make no mention of commissioning, even for Gold and Platinum projects. This situation may improve over time but it does suggest a need to be proactive in obtaining information on design and operational problems in buildings that are likely to be seen as successful.

[13] Linked from http://www.usgbc.org/LEED/Project/project_list.asp

II. Literature Review

The publications reviewed and described here fall into two categories:

- Case studies of individual buildings
- Generic lessons learned from commissioning 'green' buildings

Case Studies

The most comprehensive sources of information found are the individual reports on the six High Performance Buildings studied by the National Renewable Energy Laboratory (NREL) and also described in Torcellini et al. (2004). The 'lessons learned' sections of the reports typically include descriptions of:

- Design problems that could have been addressed in the design review phase of a formal commissioning process
- Construction, equipment and control problems that could have been identified by functional testing
- Operational problems that would have required some form of performance monitoring and/or post-occupancy evaluation for them to have been identified had NREL not performed the case study.

The first six items below summarize the commissioning-related issues identified in the NREL High Performance Buildings reports. The seventh item summarizes the commissioning-related issues identified in a case study on a showcase new office building in Berlin, Germany.

1. <u>BigHorn Home Improvement Center (Deru et al. 2005a)</u>

- No 3rd party commissioning – considered too expensive
- Lack of documentation during design and construction led to disputes about intended design and responsibilities
- Limitations of DOE-2 restricted the design
- Daylight performance was poorer than anticipated – actual glazing area less than designed, bug screens reduced transmission, dark overhangs.
- PV and inverters not designed as an integrated system - also needs automated monitoring. Poor payback as peak demand is from lighting, i.e. at night – worth installing batteries?
- Transpired solar collectors for ventilation preheat ineffective as warehouse doors open all the time.
- Poor design of hydronic systems (radiant floor and snowmelt)
- Poor light sensor placement
- Poor integration of lighting controls and EMCS (switches in series)
- Natural ventilation controls inadequate initially – need to take account of current and future outside temperatures.
- Sequence of operations for boiler and pump had to be reprogrammed
- Actuators of clerestory windows had to be rewired to work with EMCS
- General need for better performance monitoring – installed EMCS not adequate.

- Programming the EMCS an ongoing process to fine-tune the performance of the building
- Performance benefited from post-occupancy fine-tuning of system operations. This involves constant effort, which requires motivated and trained staff – absent in most buildings.

2. Cambria Office Building (Deru et al. 2005b)

- LEED Gold
- The design-build process restricts integrated design by creating a dynamic where systems are designed in series
- Daylighting performance and artificial lighting performance both poorer than expected
- Photovoltaic inverter has 18 % losses – disconnect when not in use or (preferably) replace with more efficient unit.
- Photovoltaic system needs automated performance monitoring – manual monitoring requires unsustainable effort.
- Underfloor air distribution (UFAD) system has slow response time; temperature setbacks should be small and have long start-up times.
- (Conventional) commissioning is important but does not guarantee that the occupied building will operate efficiently. Monitoring building end use energy consumption provides valuable feedback to help maintain efficient performance of systems. Two main items missed during commissioning were (that) the west energy recovery ventilator ran continuously and the HVAC fans ran continuously. These items might have been difficult to detect without looking at the end-use data. The end-use data also allowed the timing of the lighting circuits and HVAC controls to be changed to save energy.
- Performance monitoring systems need to be very robust and be actively maintained

3. Chesapeake Bay Foundation's Philip Merrill Environmental Center (Griffith et al. 2005)

- LEED Platinum
- Natural ventilation design used assumed rather than measured wind direction. Better to design for multiple wind directions and/or stack unless wind direction reliable
- Dark exposed beams and ducts reduce daylight penetration
- Photovoltaic panels shaded by exterior structure.
- Economizer omitted from design
- Desiccant wheel installed but not used
- Demand charges not taken into account when staging heat pumps
- 'Usual' commissioning activities only relate to design basis and don't accommodate changes during occupancy. Need for post-occupancy monitoring, leading to refinement of control strategies etc.

4. NREL Thermal Test Facility (Torcellini et al. 2005)

- Unique design philosophy and nonstandard equipment require special emphasis on control system design.
- Vigilant field inspection of energy features needed during construction
- Funds were available for post-commissioning tuning and alterations, which resulted in performance improvements that would not otherwise have been obtained.

5. The Adam Joseph Lewis Center for Environmental Studies, Oberlin College (Pless and Torcellini 2004)

- Heating-dominated building.
- Electric boilers used initially to preheat water for incorrectly specified ground source heat pumps – heat pumps were then upgraded to work over an extended temperature range to reduce use of electric resistance heating. Careful staging needed for remaining electric preheat.
- Atrium has poor performance, low solar heat gain coefficient
- Photovoltaic inverter problems
- Photovoltaic isolation transformer losses – replace with more efficient transformer
- Lighting control improvements identified and implemented
- Controls designer/contractor didn't understand the building
- Users didn't fully understand the control system
- Detailed monitoring is needed to fully evaluate the building and to identify additional areas of energy savings, a level of monitoring beyond the scope of typical commissioning projects.

6. Zion National Park Visitors Center (Torcellini et al. 2005)

- Passive direct evaporative cooling, natural ventilation; direct gain and noncirculating Trombe wall passive solar heating
- Differences between climate at site and weather file resulted in undersizing of cooling capacity
- Peak electric demand occurs on winter mornings: lights + space heating + water heating – stagger start-up of different loads with demand-limiting controls. This was difficult to implement, failed when controls reset after power outage, causing high peak demand. Demand-limiting controls need to be robust as one failure triggers high demand charge.
- No formal commissioning. Informal commissioning by NREL personnel on site led to multiple problems being found and fixed; probably would not have happened otherwise.
- Continuous performance monitoring allowed NREL to identify further problems and significantly reduce energy use

7. EnergieForum Berlin (Plesser 2005)

- Office building in Berlin, Germany

- 100 $kW \cdot h \cdot m^{-2} \cdot y^{-1}$ (31 $kBTU \cdot ft^{-2} \cdot y^{-1}$) target for whole building primary energy use achieved, even with some missing control schedules and heat recovery problems.
- Calibration of the various systems for building heating and cooling proved to be problematic.
- Based on measurements and thermal simulations in terms of building monitoring (calibrated simulations?), proposed solutions including new control strategies were developed and implemented. A reduction of 33 % in the energy use during the second heating season shows the positive effects of the energy and comfort monitoring and the cooperation with the management of the facility.
- Energy designers should not only support the design, planning and construction of a new building but also evaluate the commissioning process and the first years of operation.

Though not explicitly a case study, PECI's retrocommissioning of the Intelligent Workplace Laboratory at Carnegie Mellon University, identifies a number of issues that relate to the commissioning of low energy buildings (Sellers 2002):

- Detailing problems encountered with unfamiliar technology – could have been caught by a design review of the shop drawings
- Poor comfort control
- Poor make-up air system performance and reliability
- System integration problems
- Problems with coordination of control of multiple components/systems: natural ventilation, evaporative cooling, demand-controlled ventilation, radiant cooling …

Generic Lessons Learned

Berning and Grunenwald (2004) describe several problems that they encountered in the commissioning of a number of LEED-certified buildings:

- Design intent and basis of design not developed well by the design team and owner.
- Data documenting the completion of the LEED requirements is not assembled appropriately or in a timely manner by the design team at the end of the design phase
- Contractors don't submit reports – or are reluctant to do so – documenting LEED compliance.
- The project manager's ability to enforce the requirements is often reduced by the contractor's lack of understanding that this needs to be managed.

Ring and Ingwalson (2004) also describe recurrent problems encountered in commissioning 'green' buildings:

- LEED projects, especially Gold and Platinum, often include non-standard mechanical, electrical and plumbing systems, significantly increasing the effort required for commissioning.
- The commitment of the Owner is the key to success – the commissioning process and the problems it reveals can be disregarded if the owner is disengaged or unsupportive

- Unmanageable complexity should be avoided at all costs; innovative systems need to be understood by all concerned, especially O&M staff – a particular problem in small buildings
- The sequence of operation is often ambiguous – poor information provided to controls contractor who is likely unfamiliar with the systems if they are innovative. Poorly defined or documented sequences of operation make it difficult to develop functional tests.
- Daylight dimming systems require significant coordination. Most lighting designers, electrical contractors and building operators do not have enough experience with dimming systems to appreciate the issues related to sensor placement, zoning and circuiting.
- Underfloor air delivery plenums are difficult to seal for supply air control, so difficult to get good air distribution. Difficult to control supply plenum pressure in VAV systems

III. Discussion

A number of recurrent themes are evident in the ten publications cited above.

Design Problems

Designers, even when they have been selected for high visibility sustainable design projects, are often not sufficiently familiar with the even moderately unconventional strategies and systems that they employ – e.g., daylighting, ground source heat pumps, photovoltaics, evaporative cooling and natural ventilation. The design review element of the commissioning process has the potential to trap some of the problems that arise as a result of the limitations of the design team, but is not a panacea in this regard. Simulation has a potentially beneficial role to play in that provides a means of representing the expected performance of the building under different operating conditions. Properly applied, it can identify mistakes during design and can also be used to represent expected performance during commissioning. Significant differences between predicted and measured performance can then be investigated and associated with construction deficiencies, equipment malfunction, design errors, incorrect simulation inputs or inadequate models.

Another generic problem is that designs are often too complex for the skill level of the contractors and/or whoever will operate the building. This is a particular problem for small, isolated (i.e., not on a campus), buildings, since they rarely have a dedicated operator who could cope with the unique features of the building. Simpler, more robust, systems often perform better in practice than more complex systems that are more efficient on paper. This problem is a particular challenge for very low energy buildings; it is not yet clear to what extent commissioning, performance monitoring and automated diagnostics can ameliorate this problem.

Commissioning Methods Lacking for Innovative Buildings

Formal, third-party, commissioning is frequently not performed because it is seen as too expensive and the benefits are not well understood. Commissioning is thought to be appropriate for larger buildings, where economies of scale can help to reduce the cost on a floor area basis. However, many of the recent buildings designed to have very low energy consumption, and all of the US examples that have been studied in detail, are envelope-dominated, small commercial or educational buildings. As a result, daylighting and heating are more important than they would be in larger buildings; for most of the buildings, daylighting plays the most important role in the design strategy. Most of the commissioning currently performed in the United States is restricted to conventional HVAC systems in offices, schools and 'high tech' buildings. As a result, 'conventional' commissioning is often inadequate to detect problems in innovative buildings. Functional test procedures are not well established for unconventional systems and are undefined for systems that interact at the whole building level. As a result, problems are usually detected by monitoring routine operation, even when commissioning ostensibly was performed.

Operational Problems

Operational problems were detected and remedied, and energy consumption reduced, as a result of performance monitoring by outside research organizations, e.g., NREL. It would be instructive to perform case studies in which external intervention was explicitly prohibited in the first phase of the study, so as to determine the performance that occurs without outside intervention.

Controls Problems

Controls are a frequent source of problems. Many designer teams leave the design of the control strategy to the controls contractor. With few exceptions, controls contractors have little or no knowledge or experience of innovative or unconventional mechanical systems, natural ventilation, dimming controls, façade controls, photovoltaics or system integration. Commissioning can at least serve to identify problems whose nature might otherwise not be understood, which is potentially a first step to these problems being addressed.

IV. Conclusions and Recommendations

The commissioning of innovative buildings presents a number of challenges, particularly if achieving the expected energy performance is a key objective:

- Conventional new building test procedures typically do not explicitly address energy consumption at the system or whole building level.
- Conventional commissioning procedures typically do not address peak demand.
- Commissioning procedures for innovative systems are not available in libraries or guides.
- Innovative buildings are, almost by definition, 'one-of-a-kind' and require functional test procedures that are customized to the design of that unique building.

R&D needs to address these challenges include:

- Develop methods of documenting design intent that:
  - Extend to integration of systems at the whole building level
  - Can be clearly understood by design team, commissioning agents and operators

- Include a simulation model to provide a quantitative representation of the expected performance of the building
- Develop design review guidelines for low-energy buildings to help catch problems early.
- Develop functional test methods that adequately address innovative system operation and integration issues.
- Develop functional test methods that compare expected energy performance to actual energy performance during commissioning and diagnose causes of differences.

One approach to the development of functional test methods that address energy performance in 'one-of-a-kind' buildings is as follows:

- Assume that a detailed simulation model will be produced during the design phase
- For manual testing, develop methods of using this model to generate functional test procedures:
  - Identify critical operating points for system performance and interaction between systems
  - Calculate expected performance of each system at these operating points
- For automated testing, develop automated analysis procedures that compare actual performance to the predictions generated by a real-time version of the design model:
  - The commissioning agent manipulates internal loads and set-points to drive the building to critical operating points
  - An automated tool uses comparisons of different measured and simulated quantities to distinguish between different possible faults
- 'Energy commissioning' requires additional sensors to monitor energy flows:
  - Electric submetering: lights, plugs, chillers, fans, etc.
  - Thermal flows: chilled water, hot water, air

It is proposed to pursue this approach in the context of IEA Annex 47 using EnergyPlus and a research plan will be prepared and presented for discussion at the new Annex meeting.

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Chapter 5: New Functional Tests for use in Commissioning Zero and Low Energy Buildings

1. Introduction

Functional test procedures for low energy HVAC and envelope systems are being developed in the context of IEA Annex 47. Tests for the following systems were developed in 2005:

- Radiant slabs for heating
- Underfloor air distribution plenum pressure
- Demand-controlled ventilation
- Building pressurization

An overview of each test is presented below. These and other test procedures developed in the context of the Annex will be posted on the US team website.[14]

2. Radiant Slab Functional Test

Radiant floor heating is a strategy long utilized in residential construction that is becoming more commonplace in commercial applications. It is an effective heating strategy for large open zones with high ceilings like lobbies, atriums, auditoriums, warehouses, light manufacturing facilities, and gymnasiums. However, it is also being installed in more "traditional" commercial spaces like office buildings due to the efficient use of energy and space, as well as reduced maintenance, associated with the system. A radiant floor heating system can be difficult to control due to the large thermal mass associated with the concrete slab and its slow response to load variations. In addition, the radiant floor heating system may need to interact with a conventional air handling system designed to provide ventilation and humidity control to the space. This procedure allows the verification of proper operation of a radiant floor heating system, but does not directly address the testing of ancillary HVAC equipment that may operate in conjunction with the radiant floor to supply ventilation or supplemental heating/cooling to the zone. This procedure involves:

- Ensuring all system verification checks are complete prior to executing radiant floor heating system tests
- Verifying system responds per the design sequence of operations
- Verifying actual system control through long-term trending

3. Underfloor Air Distribution Plenum Pressure Test

The primary objective of testing both the underfloor and return air plenums is to quantify the air leakage rate from each plenum, identify the leak source(s), and facilitate repair as necessary. Having a relatively leak-free plenum will reduce central HVAC supply fan energy usage, prevent system operational problems, and minimize comfort problems.

[14] http://www.nist.gov/annex47/

The procedure involves:

- Ensuring all system verification checks are complete prior to executing system tests
- Quantifying the air leakage rate from both the underfloor plenum and occupied space/return plenum
- Identifying the source of air leaks and repairing them as best as possible

4. Demand-Controlled Ventilation

A demand-controlled ventilation control strategy adjusts the quantity of outdoor ventilation air supplied by a central air handling unit based on the ventilation rate required to provide adequate indoor air quality. A significant amount of heating and cooling energy can be saved by supplying just enough ventilation air to satisfy zone load requirements. The objective of testing the demand-controlled ventilation control strategy is to ensure that outdoor ventilation air is adjusted as necessary to meet zone loads as they vary with time. The procedure involves:

- Ensuring all system verification checks are complete prior to executing system tests
- Verifying demand-controlled ventilation control strategy operates as intended for both constant and variable air volume air handling systems
- Verifying minimum ventilation air requirements are met under varying operating conditions
- Verifying that the demand-controlled ventilation control strategy interacts with the economizer control sequence correctly

5. Building Pressurization

The test is designed to help diagnose and quantify the air tightness of the whole building envelope by putting air-handling systems in 100 % outdoor air mode to pressurize the building. It is important for all buildings, but is even more critical for low energy buildings. The test is based on ASTM Standard E-779-99, but is less rigorous. The ASTM standard requires pressure measurements on every face of the building and on every few floors. It also advances the pressure in very small increments up and back. A more practical test is needed, one which could be performed more rapidly (and thus at a lower cost). By using commissioning grade measurements, rather than research-grade measurements, accuracy is sacrificed in order to have a more practical test procedure. Preparation is essential when performing a building pressure test. The Precautions section and the Prerequisites section describe the most important considerations, including verifying safeties, selecting appropriate test conditions, finding pressure measurement locations, and setting up the HVAC systems for the test. After the test is performed, the Acceptance Criteria and the Analysis of Test Data sections help quantify the energy impact of leaks and provides avenues to address problems with air tightness that are identified.

Conclusions

This report presents the state of the art in four areas where further research and development are necessary to improve the knowledge, procedures and tools that support the provision of effective commissioning services: cost-benefit methodologies, the persistence of benefits, automated commissioning tools, and the needs and challenges in commissioning zero energy buildings.

The following are specific R&D recommendations in each of the four areas:

Cost-benefit methodologies

- Develop a standardized methodology for evaluating commissioning costs and benefits.
- Create a data collection instrument that allows respondents to easily submit their project information and incorporates an automated or semi-automated analysis tool.
- Fund an ongoing data collection and analysis effort.

Persistence of benefits

- Develop a uniform methodology for determining commissioning persistence
- Determine the persistence of savings from a broader sample of buildings
- Develop simple tools for tracking performance of commissioning measures
- Develop practical methods for owners and operators to better maintain commissioning savings

Automated commissioning tools

- Develop user-demanded features in automated commissioning tools, including automatic generation of documentation with cost information based on standard calculations.
- Implement information models for building systems to reduce the information loss and enable automated use of data as a building advances through design, construction, and operation.
- Extend methods and tools, for additional building systems, to speed up the process of preparing a commissioning plan, ensure compliance with standards/guidelines, and help ensure consistency across projects

Commissioning zero energy buildings

- Develop methods of documenting design intent and performing design reviews that are adapted to the specific needs of innovative and low energy buildings
- Develop functional test methods that adequately address innovative system operation and integration issues.
- Develop functional test methods that compare expected energy performance to actual energy performance during commissioning and diagnose causes of differences.

- Incorporate simulation in functional testing as a means of enforcing accountability for energy performance between design and construction

Commissioning has a key role to play in comprehensive quality assurance for the design, construction and operation of buildings. Although commissioning is a valuable means to ensure that a building reaches its operating potential, it has not been widely adopted. Overcoming the market barriers to the adoption of commissioning is becoming progressively more important as the number of buildings employing innovative, interactive systems increases. The need for commissioning is especially acute when these systems are installed in low or zero energy buildings.

Appendix: Automated Commissioning Tool Interfaces

ENFORMA – Architectural Energy Corporation

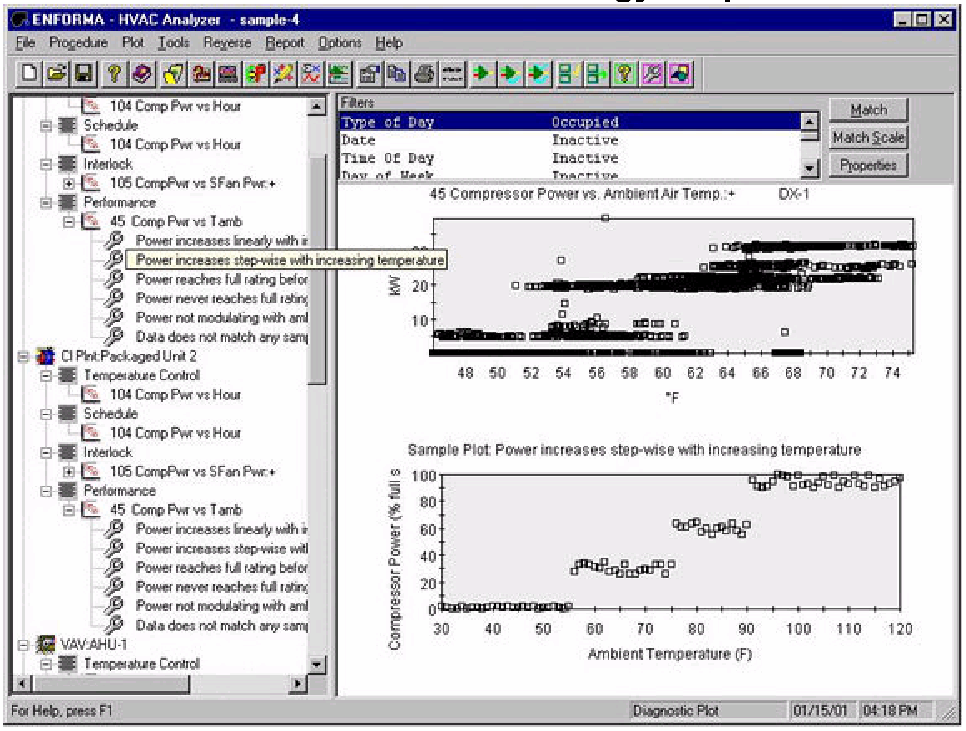


Figure A.1. Diagnostic Plot shows the power draw for the roof-top unit with the properly operating economizer.

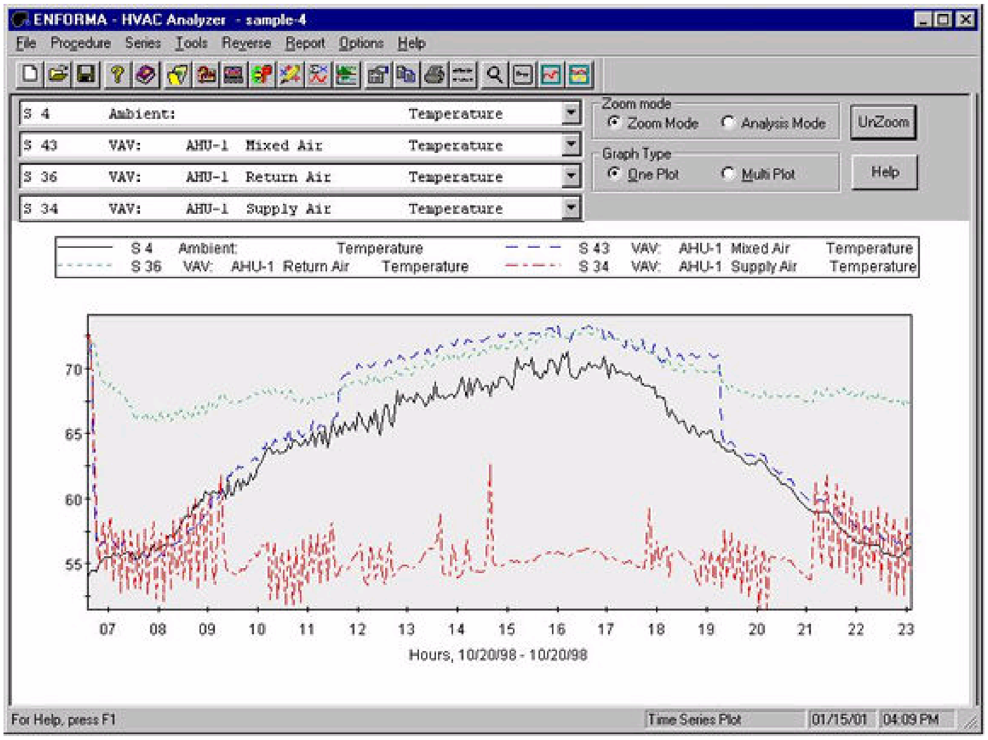


Figure A.2. ENFORMA RTU plot

PACRAT- Facility Dynamics Engineering

Facility Dynamics
EVERYTHING IS UNDER CONTROL

Apparent Anomalies

GSA-R9-CA0281ZZ - Oakland_FB

Report generated on 8/28/2006

AHU Key	Devices	Entry Date	Date Range	Consequence	$ Waste	Priority
OFB_SAH_PH-South Tower DD AHU					**$18,694.46**	**19,492.00**

> Unit operating during unoccupied times

* Fan OA D	8/27/2006	1/1/2006 - 8/5/2006	Energy Waste	$15,847.92	15,848.00

The unit is operating during the unoccupied period. Unoccupied fan operation while the space temp was between the setback setpoints cost $15700. The cost to condition the ventilation introduced was $148. The unit ran 34% of the scheduled unoccupied hours.

> Lack of economizer

* OA D	8/27/2006	1/1/2006 - 8/5/2006	Energy Waste and IAQ	$2,168.31	2,168.00

Airside economizer oppurtunities are being missed due to poor programming.All of the indicated wasted cost was when OA was above 35°F.

> Excess outside air during the occupied period

* MinOAD_C Fan	8/27/2006	1/1/2006 - 8/5/2006	Energy Waste	$678.23	678.00

Excess outside air was introduced during occupied periods. 117 daily periods were found where the average OA flow during that period averaged unnecessarily high. The cost waste associated with periods of cooling was $20. The cost waste associated with periods of heating was $657. The average excess OA flow for the periods when it was identified was 7457.

> Sensors non-representative

* MA_T_Avg M_OAT	8/27/2006	1/1/2006 - 8/5/2006	Affects other conclusions	$0.00	159.00

The MA, RA, and OA sensors indicate either that 1) one of the sensors is not in a stable representative position (probably the MA), or 2) one of the control loops is unstable. This is based on there being a significant amount of time when the MA sensor is both higher than the other two (an average of 1.6 degrees and lower than the other two (an average of 0 degrees)

> Sensor failure

* kCFM_Diff	8/27/2006	1/1/2006 - 8/5/2006	Control and Conclusions	$0.00	16.00

The kCFM_Diff sensor was failed from 1/10/2006 11:00:00 AM to 7/8/2006 1:00:00 AM 8% of the time. It showed an average value of -21.3.

> Suspect sensor readings

* HD1_F	8/27/2006	1/1/2006 - 8/5/2006	Control and Conclusions	$0.00	29.00

The HD1_F sensor was suspect from 1/5/2006 10:30:00 AM to 4/13/2006 8:45:00 AM 14% of the time. It showed an average value of 0.

Figure A.3. Sample PACRAT Anomaly Report Output

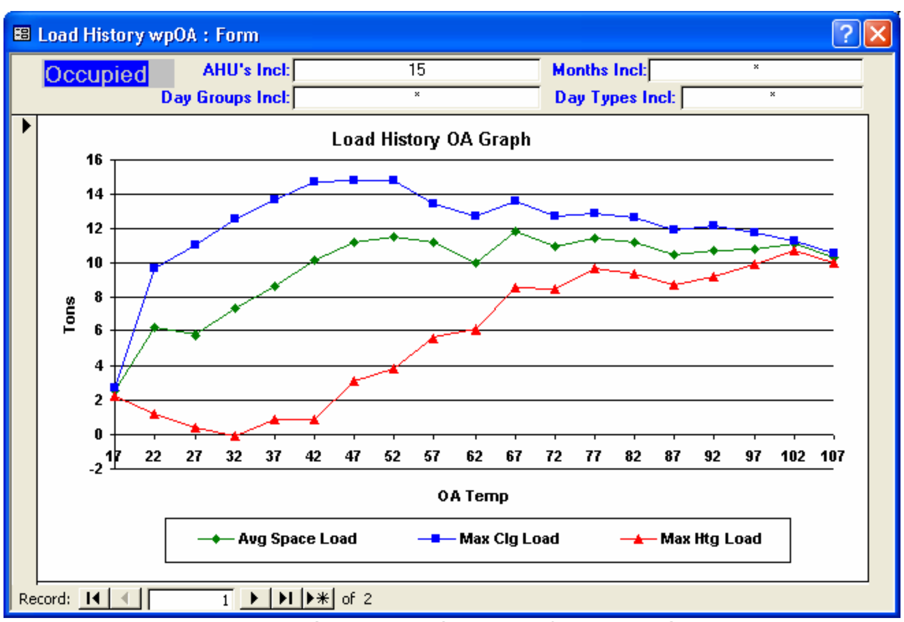


Figure A.4. Sample PACRAT Performance Graph

Virtual Mechanic

Figure A.5. Virtual Mechanic hardware

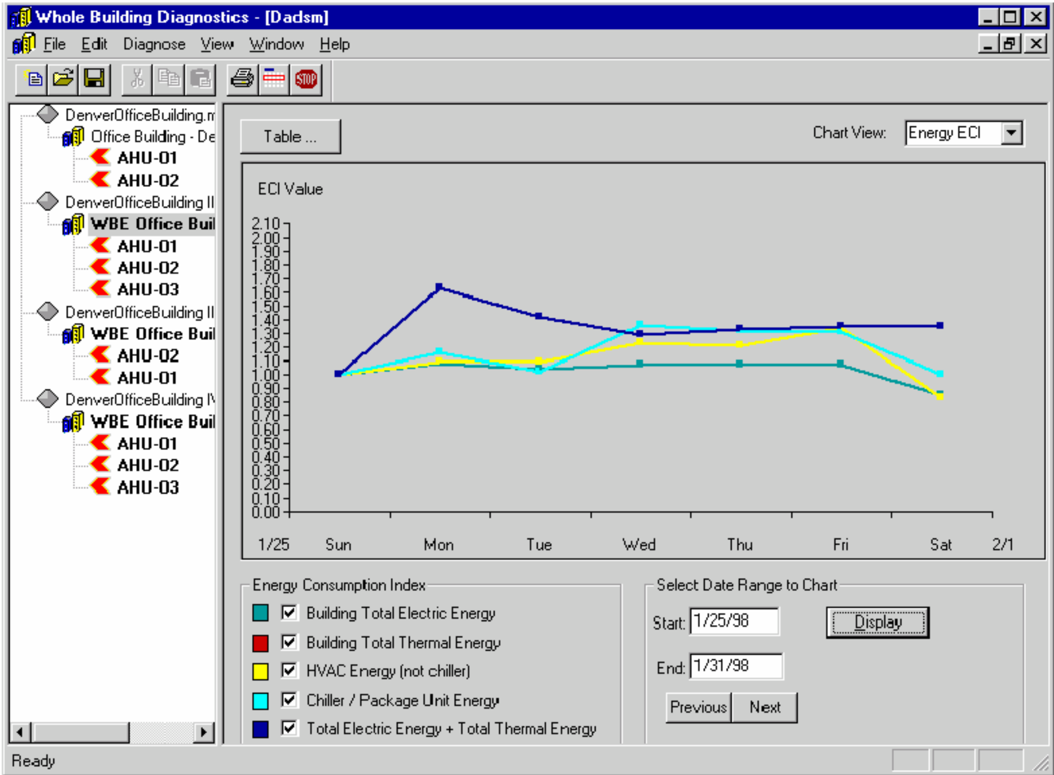


Figure A.6. Sample Energy Performance Chart

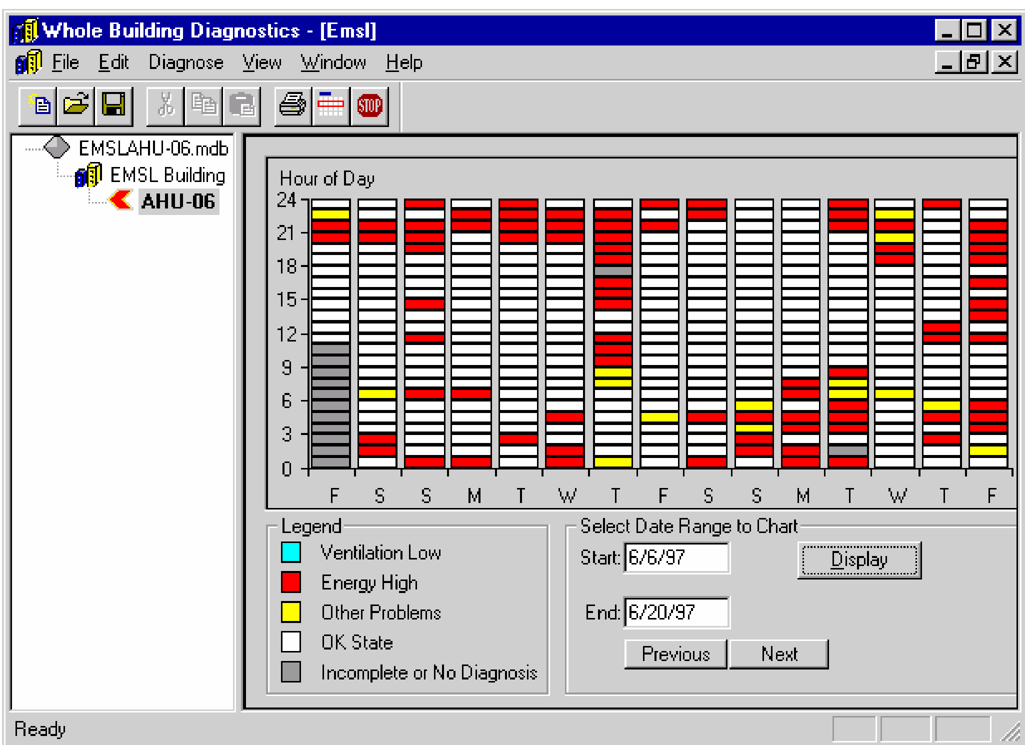


Figure A.7. Sample Diagnostics Report

DABO- Natural Resources Canada

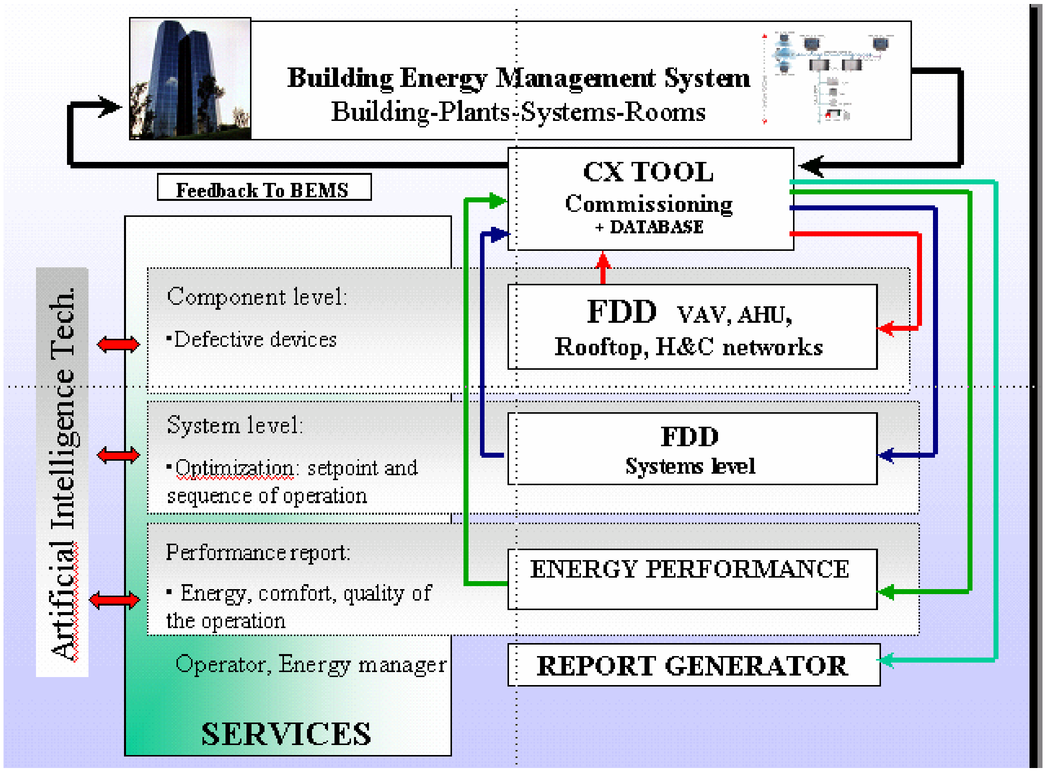


Figure A.8. DABO tool

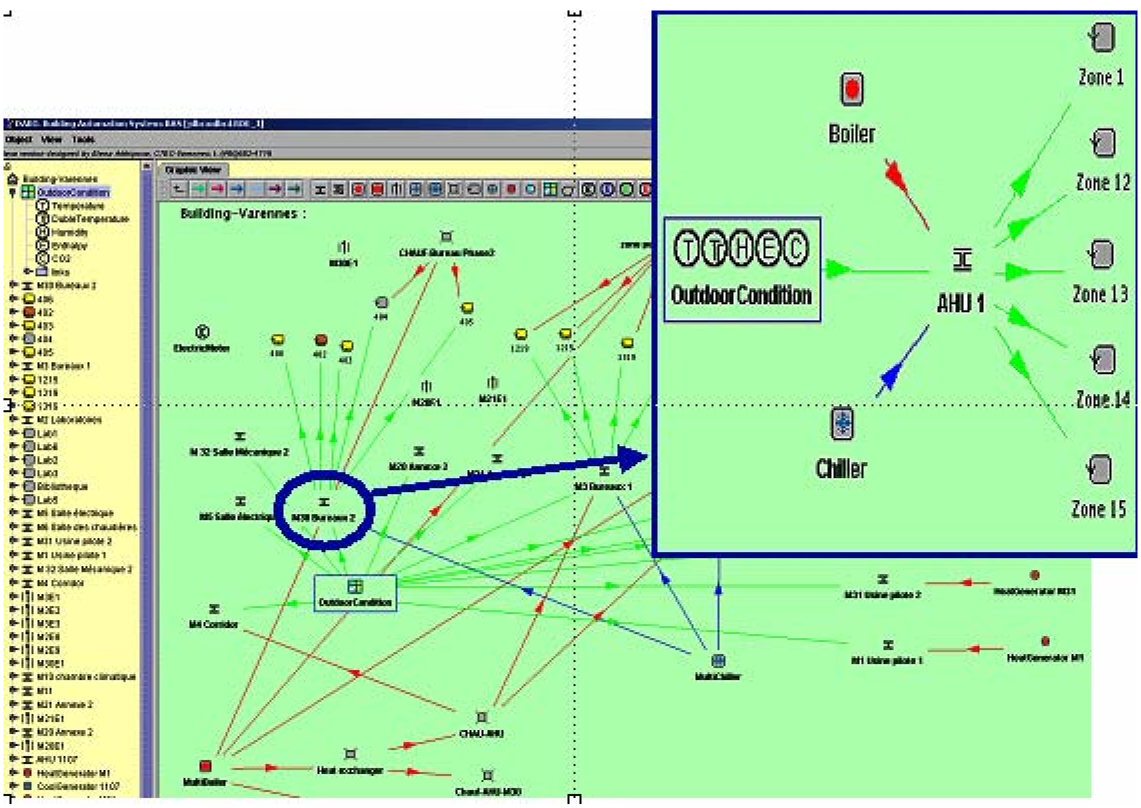


Figure A.9. DABO Configuration Interface

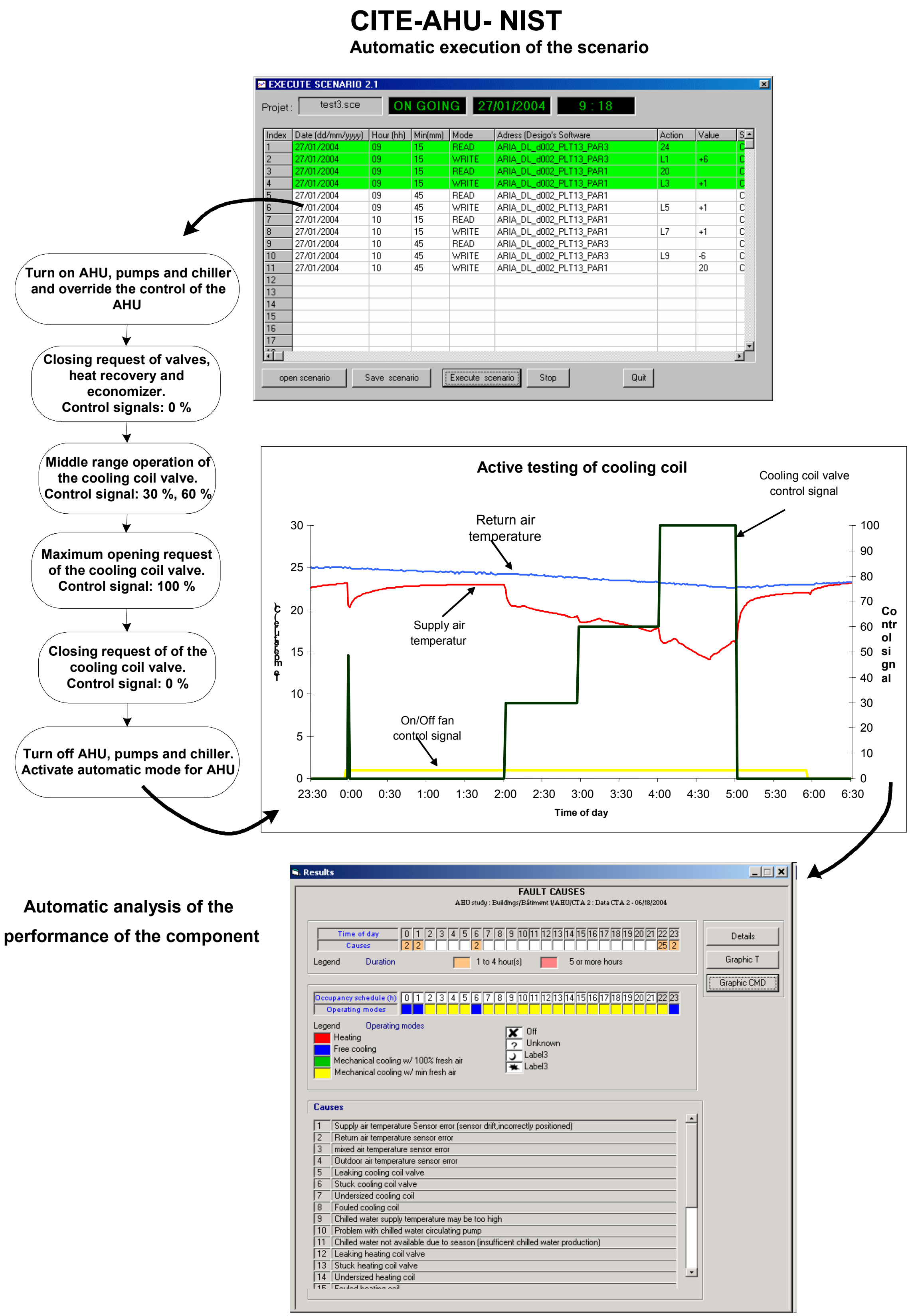


Figure A.10. Overview of test sequence and analysis

LBNL Tool

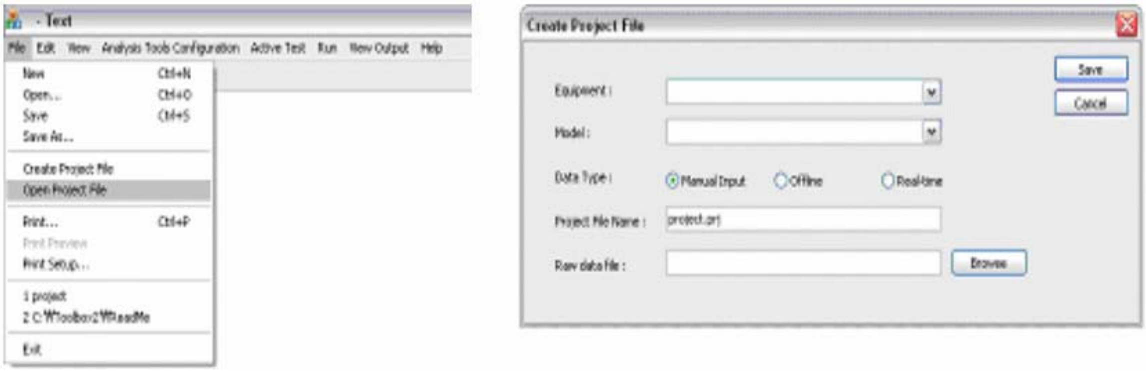


Figure A.11. Project Set-up Interface

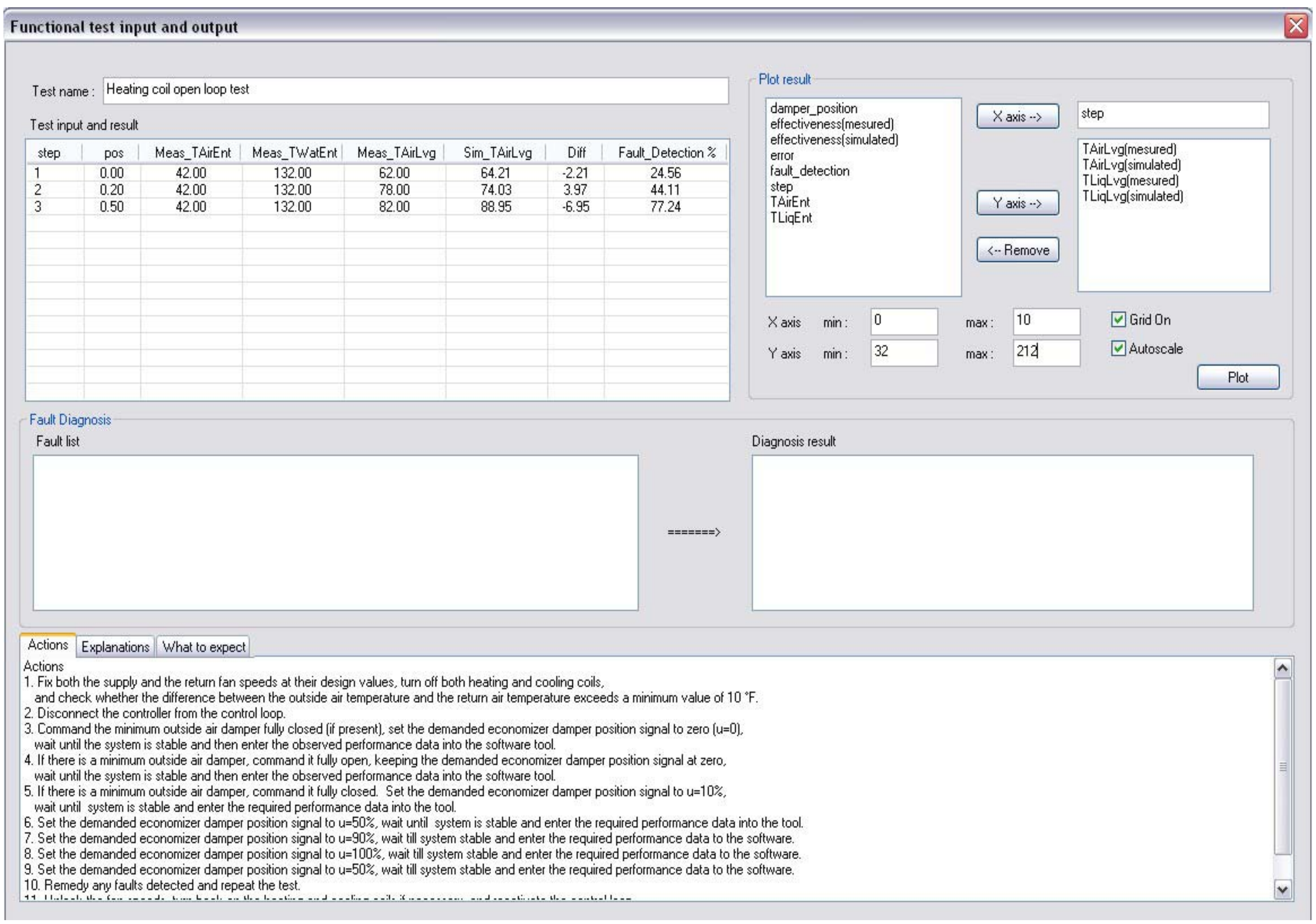


Figure A.12. Draft GUI of the *Functional test input and output* submenu

WebE

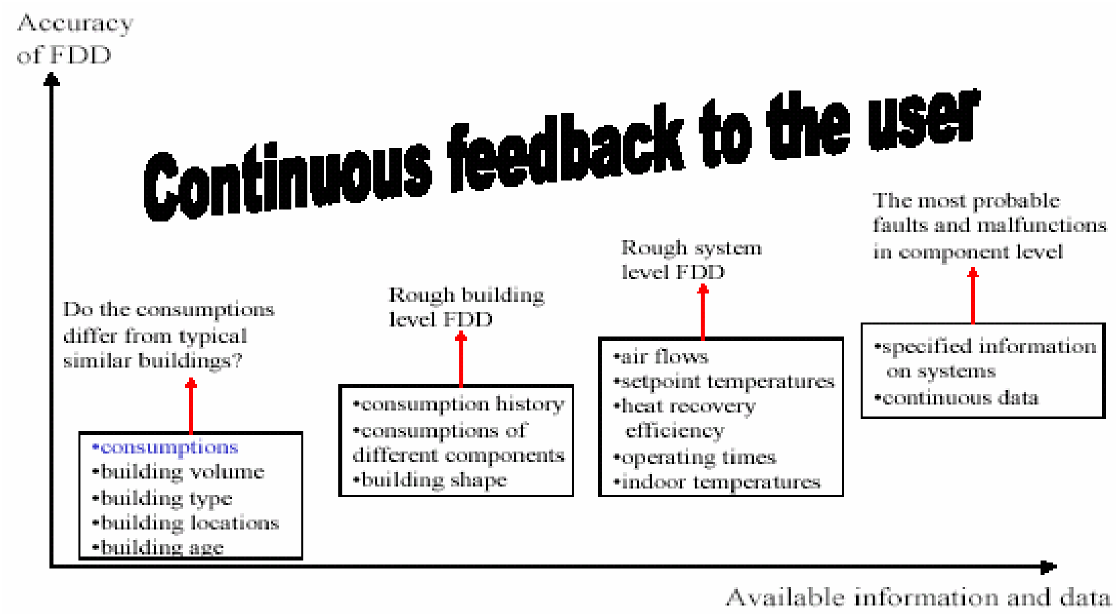


Figure A.13. Fault Detection and Diagnostic Approach

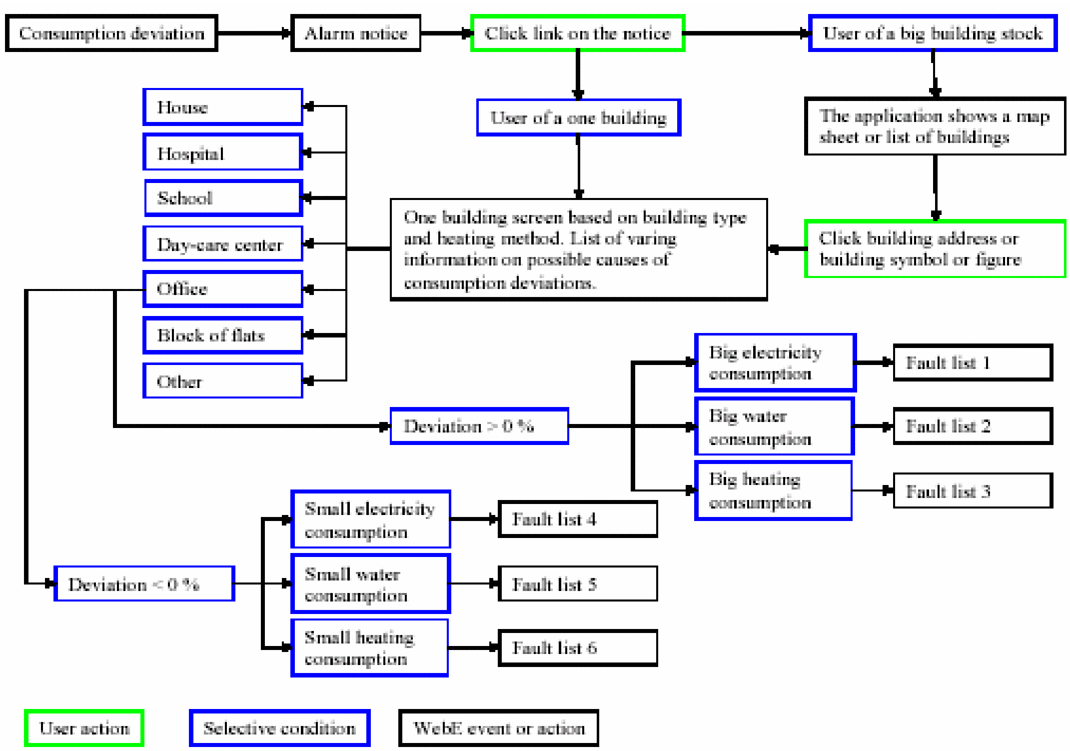


Figure A.14. A flowchart of the FDD/Commissioning Module

EnergyWitness

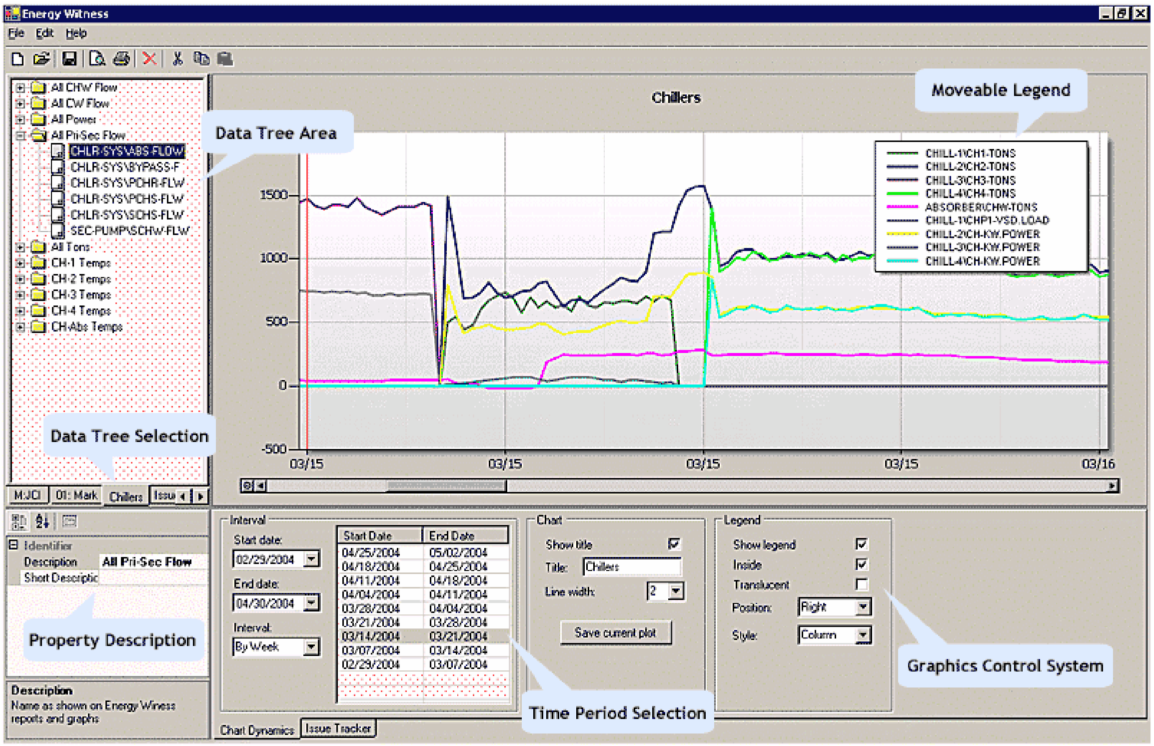


Figure A.15. Trending capabilities for data.

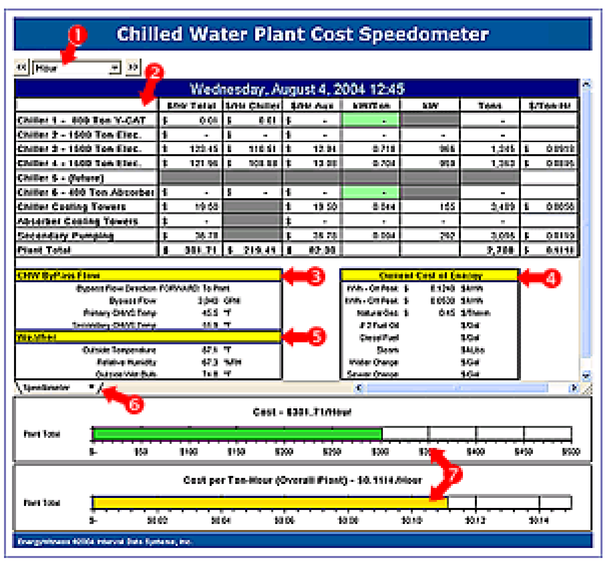
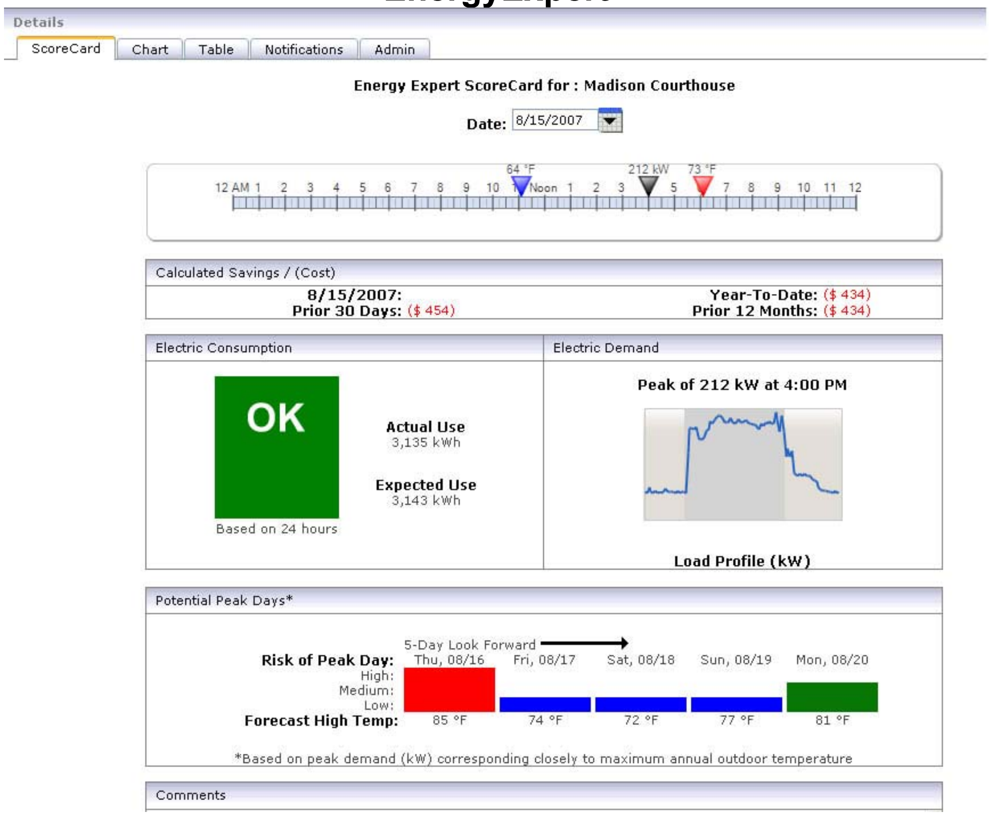


Figure A.16. Chilled Water Plant Speedometer.

Operators can move through time (1) and see data for each system and the entire plant (2). Bypass flow (3), energy rates (4), and weather data (5) are shown. A tab (6) switches the view to show the underlying models. Gauges show total in $/hr and $/ton-hr (7).

EnergyExpert



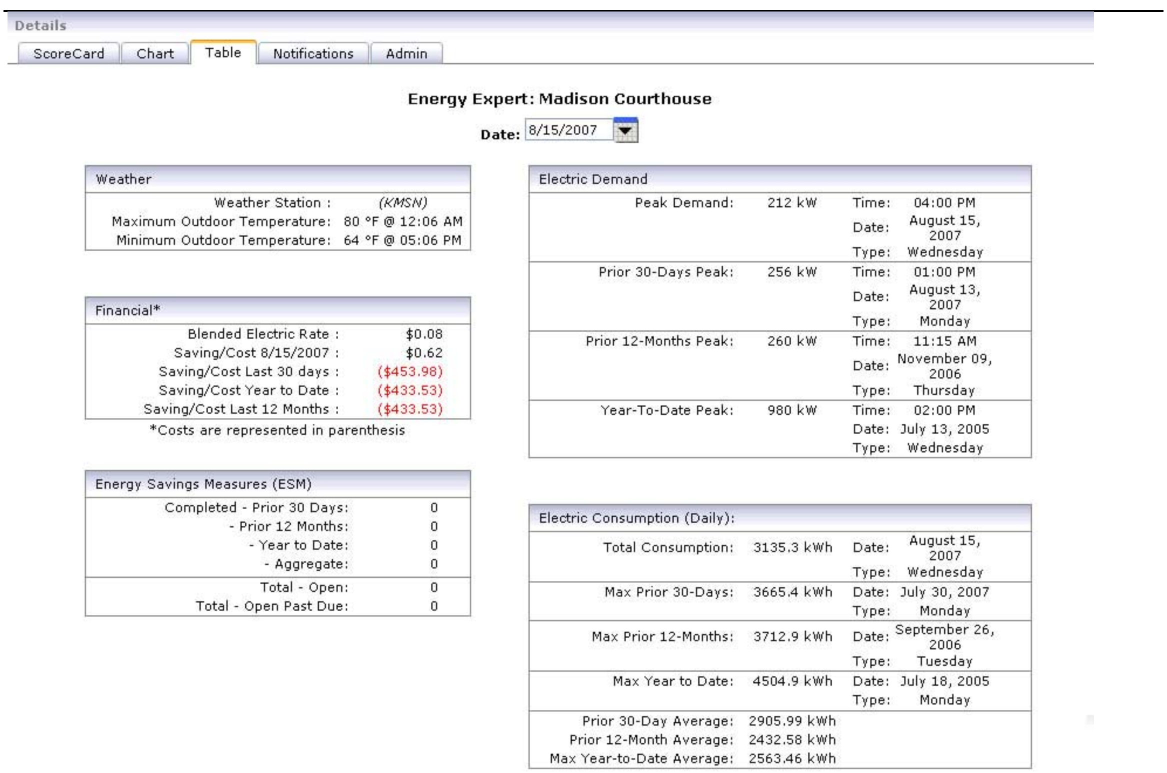


Figure A.17. Energy Expert screen shots for Scorecard report (top), and tables (below).

Control Logic Tracer

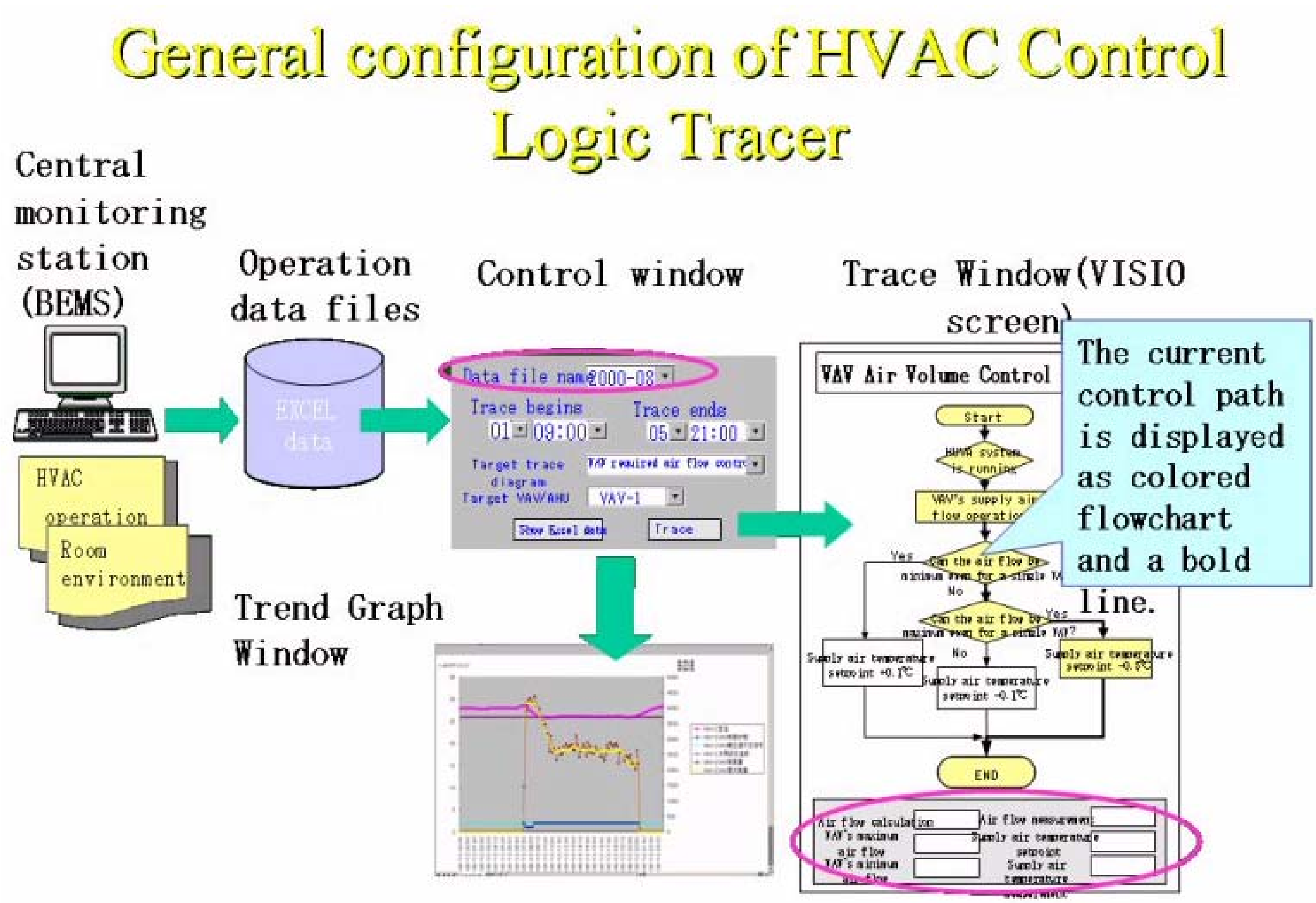


Figure A.17. Flow chart of Control Logic Tracer operation.